Ecology and climate sensitivity of a groundwater-fed lake on subtropical North Stradbroke Island (Minjerribah), Queensland, Australia over the last 7,500 years

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Abstract

Lake sediments are important archives of past climate variability and lake responses to climate. In order to accurately infer past climates, it is necessary to understand, and account for, the ecological processes that affect the record of indicators preserved in lake sediment. This is particularly the case with respect to the concentration of carbon and nitrogen (TOC, TN, and calculated C:N), and the stable isotope composition of organic matter preserved in lake sediments. These are common, yet ambiguous, tracers of environmental change. Ideally, palaeoenvironmental reconstructions using the concentration and isotope composition of organic matter should be grounded in a detailed understanding of the sources of the organic material. This study documents the history and evolution of Blue Lake, an environmentally and culturally important oligotrophic, groundwater window lake on North Stradbroke Island, Queensland, Australia. We utilise organic matter $\delta^{13}C$, TOC, TN, and C:N from a 2.4 metre sediment core with a basal age of 7.5 cal kyr BP, to investigate changing organic matter sources as a measure of the climate sensitivity of Blue Lake. This interpretation is supported by data from contemporary algae, aquatic and terrestrial plants, and catchment soils. We show that lake nutrient dynamics drove an increase in algal biomass at 4.2 cal kyr BP. This change coincides with a widely documented intensification of the El Niño-Southern Oscillation, which we infer to have influenced lake nutrient concentrations by reducing groundwater throughflow. Climatic changes resulted in marked changes in lake primary productivity, despite relatively little turnover of the lake diatom flora and catchment vegetation. This suggests that south-east Queensland dune lakes are sensitive to climate changes and helps to refine past and future palaeoclimate research using sediments from these lakes. It also indicates that increased nutrient concentrations in Blue Lake may result from projected changes in 21st Century climate.

Introduction

Climate change is a severe threat to global freshwater systems, affecting both the number and ecological health of aquatic ecosystems (Paerl and Paul 2012; Jun et al. 2011). This is especially problematic in mainland eastern Australia where there are few permanent freshwater lakes due to the aridity and lack of recent tectonic and glacial activity (Bridgman and Timms 2012). Most natural lakes in mainland eastern Australia are dune lakes (Chang et al. 2014), with over 250 concentrated in the south-east Queensland dune field (Hembrow et al. 2018; Tibby et al. 2017). Projected reductions in effective moisture (Grose et al. 2020; King et al. 2017) are a threat to these lakes which harbour unique species and ecology (Page et al. 2012).

The major influence on eastern Australian climate is the El Niño-Southern Oscillation (ENSO) coupled ocean-atmosphere climate system which has far reaching global effects (Dai and Wigley 2000; McPhaden et al. 2006). While inter-annual changes in ENSO are well documented, variation at decadal to millennial scales is less well understood. Studies across the Pacific documenting ENSO variability over millennial timescales have identified an intensification in ENSO activity in the late Holocene (Cobb et al. 2013; Conroy et al. 2008; Koutavas and Joanides 2012; Moy et al. 2002; Tudhope et al. 2001). However, uncertainties persist regarding the timing of ENSO intensification and the expression of that change in eastern Australia, at the western margin of the Pacific Ocean. In this respect, Blue Lake on North Stradbroke Island (Fig. 1) is a well-placed site to study both ENSO variability and lake ecosystem responses to changes in that variability. A study that reconstructed rainfall from Swallow Lagoon (Fig. 1B), approximately five kilometres from Blue Lake, has been interpreted as sensitive to millennial scale ENSO mean state (Barr et al. 2019). The proximal location of Swallow Lagoon and quantitative precipitation record provides facilitates an analysis of the response.

The elemental (C, N and calculated C:N ratio) and carbon isotope ($\delta^{13}C$) compositions of lacustrine organic matter are a common and often powerful palaeo-environmental tracer, sensitive to both catchment and within-lake change (Meyers and Lallier-Vergès 1999). As is the case with all palaeo-environmental proxies, the interpretation of bulk organic matter geochemical tracers should be underpinned by a clear, geographically relevant understanding of the processes that led to their deposition in the sediment record. However, such studies are relatively uncommon for the humid subtropics (Escobar et al. 2020). A previous low-resolution study from Blue Lake interpreted a decline in sedimentary C:N and $\delta^{13}C$ in the mid-Holocene to reflect a climate-driven change in the dominant source of organic matter, from terrestrial to aquatic origins (Barr et al. 2013). This interpretation was mainly based on observations made in lake systems around the world, that have found that aquatic organic matter tends to have C:N ratios less than 10 and lower $\delta^{13}C$ (Meyers and Lallier-Vergès 1999; Mayr et al. 2009). However, a recent study that analysed modern samples from four North Stradbroke Island wetlands, including a small number from Blue Lake, argued that this interpretation of C:N ratios is not applicable in low nutrient environments where algal derived organic matter can have C:N ratios >20 (Cadd et al. 2018). The first aim of this paper is, therefore, to examine in detail the association between the sources of organic matter in the Blue Lake sediments and their C:N and $\delta^{13}C$ signatures through an intensive modern survey. The second aim is to revisit the nature of Holocene environmental change at Blue Lake through analysis of a new, high-resolution record of TOC, TN, C:N, and $\delta^{13}C$ of sediment organic matter from a 2.4-metre sediment core, spanning the last 7500 years (7.5 kyr before present (BP), where 'present' is 1950). In particular, by improving both the resolution and chronology, the Blue Lake record can be examined in the context of a recent rainfall reconstruction based on monospecific leaf $\delta^{13}C$ analyses at nearby Swallow Lagoon (Barr et al. 2019).

C:N and $\delta^{13}C$ of organic matter in lake sediments

The sources of organic matter in sediments are traditionally distinguished by C:N ratios and $\delta^{13}C$ (Meyers and Ishiwatari 1993; Cadd et al. 2018; Contreras et al. 2018; Liiv et al. 2019). Terrestrial plants have relatively higher proportions of carbon rich structures such as lignin and cellulose and generally have C:N >20 (Meyers 1994). In fire prone landscapes, including Australia, charcoal may be an important component of sedimentary organic matter (Bird et al. 2015). Charcoal has low C and $\delta^{13}C$ relative to source wood due to the breakdown of structural components (Ferrio et al. 2006; Bird and Ascough 2012). In aquatic algae, structural carbon is found in lower concentrations and nitrogen in higher concentrations to aquatic macrophytes and terrestrial plants (Meyers and Teranes 2002). Aquatic macrophytes tend to have intermediate carbon and nitrogen concentrations to algae and terrestrial organic matter (Meyers and Teranes 2002). Diagenetic changes in C:N and $\delta^{13}C$ in lake sediments are not thought to be large enough to eliminate the differences between different organic matter sources (Meyers and Teranes 2002; Smith et al. 2017). Therefore, organic matter degradation and diagenesis are unlikely to markedly alter the C:N and $\delta^{13}C$ of sedimentary organic matter (Meyers 1994; Gälman et al. 2008).

Interpretation of lake sediment $\delta^{13}C$ reflects several different processes. Changes in organic matter source, the mixture of different sources of organic carbon, and the effects of productivity on the $\delta^{13}C$ of photoautotrophs will alter the $\delta^{13}C$ of sedimentary organic matter in lakes (Leng et al. 2006; Leng and Marshall 2004; Brenner et al. 2006). Terrestrial and aquatic plant $\delta^{13}C$ varies based on the photosynthetic pathway used, but are generally $-33‰ > \delta^{13}C < -22‰$ (C_3), $-15‰ > \delta^{13}C < -10‰$ (C_4), or $-30‰ > \delta^{13}C < -10‰$ (CAM), with $\delta^{13}C$ of algae generally falling in the C_3 plant range (Meyers and Teranes 2002; Cernusak et al. 2013).

Sedimentary $\delta^{13}C$ values can be used to reconstruct water column primary productivity where the dominant source of organic matter is autochthonous (as indicated by low C:N) (Mayr et al. 2009; Brenner et al. 1999). In this context, algae and aquatic plants preferentially fix ^{12}C from DIC of lake waters, which reflects the $\delta^{13}C$ concentration in the atmosphere (Leng et al. 2006). Algae and submerged aquatic plants typically produce organic matter that is – 20‰ relative to ambient DIC (O'Leary 1988; Wolfe et al. 2002). Primary production generally enriches the water column in ^{13}C, as autotrophs preferentially take up ^{12}C (Leng et al. 2006). High growth rates of primary producers accelerate water column ^{13}C enrichment (Laws et al. 1995), which can lead to rapid changes in $\delta^{13}C$ of the DIC and sedimentary organic matter.

Research on the south-east Queensland dune field lakes, principally from Fraser Island (K'Gari in the language of the traditional owners) and North Stradbroke Island (Minjerribah), including a low-resolution study from Blue Lake (Karboora) (Barr et al. 2013), have used C:N and $\delta^{13}C$ to identify sources of organic matter in lake sediments (Atahan et al. 2015; Hembrow et al. 2014; Hembrow et al. 2018; Barr et al. 2017). All these studies found sedimentary $\delta^{13}C$ values in the C_3 plant range, and most interpreted C:N >10 as indicative of terrestrial vascular plant material (Barr et al. 2013; Barr et al. 2017; Atahan et al. 2015; Hembrow et al. 2014; Hembrow et al. 2018). However high C:N sediment values were, in part, indicative of the colonial green algae *Botryococcus*. *Botryococcus* has high carbon and lipid content relative to nitrogen, leading to high C:N (with values >100 recorded) (Heyng et al. 2012) that contribute to increased sedimentary C:N. A recent investigation of C:N and $\delta^{13}C$ in modern plants and algae on North Stradbroke Island reported C:N values for five algae samples which were higher than expected (mean C:N = 24) which, in turn, was interpreted to reflect nitrogen limitation of sand island plants and algae (Cadd et al. 2018). Cadd et al. (2018) suggested that C:N >20 could be derived from algae, macrophytes, or terrestrial plants, and care must be taken when interpreting sedimentary C:N records from sand island lakes.

Climate driven ecological changes in lakes

The principal sources of energy to lakes are light, nutrients, and organic matter availability (Gagliardi et al. 2019; Staehr et al. 2012; Brothers et al. 2013). These, in turn, are controlled by the physical, biological, and chemical characteristics of lakes and their catchments, which are ultimately influenced by climate (McGowan et al. 2018; McGowan et al. 2008; Leng et al. 2012; Stockwell et al. 2020). Climate controls lake processes through temperature (Kilham and Kilham 1990; Lewis Jr 2010; Fritz and Anderson 2013) and precipitation (Gagliardi et al. 2019; Stockwell et al. 2020). Precipitation influences lake behaviour via changes in lake depth, water residence time, nutrient runoff (including N, P, and DOC), and the balance between groundwater and catchment waters (Hayes et al. 2015; Stockwell et al. 2020; da Costa et al. 2016; Brasil et al. 2016; Périllon and Hilt 2016; Karthe 2018). Similarly, temperature can influence lakes through evaporation, lake thermal structure, the length of ice-free periods and via its fundamental influence on species abundances and growth rates (Joung et al. 2017; Andersen et al. 2017; Tal 2019). The combination of these factors differs between lakes and these differences can be recorded in sedimentary C:N and $\delta^{13}C$ which, in turn, can elucidate the processes that drive lake ecological change.

Climate can influence sedimentary organic matter C:N and $\delta^{13}C$ through soil and nutrient in-wash, catchment or groundwater influx, and changes in lake pH (Stockwell et al. 2020; Meyers and Teranes 2002). Soil and nutrient in-wash and groundwater and river influxes can increase nutrient inputs, and therefore productivity in lakes, increasing the $\delta^{13}C$ of sediment organic matter. If lake productivity is low, in-washed terrestrial material has a greater influence on sedimentary C:N and $\delta^{13}C$ with sedimentary C:N ratios increased due to the presence of carbon rich terrestrial material. Groundwater and river influxes can alter water residence times, which increases productivity as residence time increases due to high concentrations of nutrients to the water column (Gagliardi et al. 2019) and vice versa. Precipitation and temperature-driven changes in lake level can alter lake pH such that the dominant dissolved carbon species change, altering primary producer metabolism (Leng et al. 2006).

Study site

North Stradbroke Island (Minjerribah) (27°27'S, 153°28'E) is located off the coast of eastern Australia, in the subtropical climate zone, with warm summers (mean 26°C) and mild winters (mean 19°C) (Bureau of Meteorology 2020) (Fig. 1). Annual rainfall is ~1500 mm and is summer dominated with only 15% of rainfall occurring between July and October (Bureau of Meteorology 2020). At inter-annual scales, ENSO phases have a strong influence on regional rainfall (Barr et al. 2019; Risbey et al. 2009), with El Niño events associated with lower rainfall and La Niña events characterised by higher rainfall (Klingaman 2012).

North Stradbroke Island is the second largest sand island in the world and is part of the larger south-east Queensland dune fields that include Fraser, Bribie, and Moreton Islands, and the Cooloola sand mass (Patton et al. 2019). North Stradbroke Island was formed during several dune building phases over the last 500 kyr (Patton et al. 2019; Lewis et al. 2021). The dune building phases occurred predominantly during periods of marine transgression via aeolian transport of continental and exposed marine sands (Lees 2006; da Silva and Shulmeister 2016; Patton et al. 2019). The island topography is composed of vegetated, parabolic dunes oriented NW-SE reflecting the prevailing south-westerly wind direction. The lakes and wetlands on North Stradbroke Island are the surface expression of the many local perched aquifers, or the regional aquifer (Barr et al. 2013; Leach 2011; Marshall et al. 2011). Perched wetlands and their localised aquifers form from accumulated organic material in dune hollows that, through the podzolization process, creates a horizon of impermeable, cemented sand (Timms 1986; Reeve et al. 1985; Cadd et al. 2018).

By contrast, Blue Lake (27°31'S, 153°28E) is a groundwater "window" lake that intersects with the regional (island) groundwater table. The lake has a maximum modern water depth of 11 m, is polymictic, and has an average pH of 4.95 (Barr et al. 2013). Blue Lake is classed as oligotrophic due to its low total phosphorus and nitrogen (mean 4 mg m^{-3} and 120 mg m^{-3} respectively), low chlorophyll α (mean 1.93 mg m^{-3}), and high Secchi depth (mean 5.73 m) (Barr et al. 2013; Carlson 1977). Water quality data collected monthly from Blue Lake over seven years between January 1996 and November 2002 shows evidence for N limitation (Barr et al. 2013). Using the Redfield ratio of 16:1 N:P as a threshold, these data show that Blue Lake was N limited for 70% of the monitoring period. Water clarity is high and allows light penetration to the sediment surface in all locations (Barr et al. 2013). The lake level is primarily controlled by groundwater inflow and the elevation of a swamp that forms the outflow barrage on the south-east edge of the lake (Barr et al. 2013). The presence of a permanent outflow stream indicates that inputs to the lake are greater than water losses. Modelled stream outflow, bathymetric surveys, and aerial photography over a 50-year period indicate that Blue Lake has varied by less than half a metre, in contrast to other North Stradbroke Island lakes which varied by up to 9 metres over the same time (Barr et al. 2013). Blue Lake is inferred to have had stable water levels throughout its history and this feature is quite rare throughout Australia (Barr et al. 2013).

The vegetation of the Blue Lake catchment is dominated by *Eucalyptus* and Casuarinaceae canopy tree species with sub-dominant communities of *Banksia*, *Melaleuca*, and various heath species (Barr et al. 2013). Aquatic vegetation is dominated by the emergent macrophyte *Lepironia articulata* (Retz.) Domin and the submerged *Eleocharis difformis* S.T.Blake with small communities of *Cycnogeton procerus* (R.Br.) Mering & Kadereit, *Gahnia* sp., and *Myriophyllum* species. The soils of the Blue Lake catchment are sandy podzols that characterise the south-east Queensland sand mass (Chen et al. 2015). They have low organic content and low soil productivity (ESM1 Fig. 4) (Stephens and Sharp 2009). The hills surrounding Blue Lake are steep and forested with patchy leaf litter above the sandy soils (ESM1).

Methods

Core collection

Two core records were recovered from Blue Lake, one in May 2007 (Barr et al. 2013) and one in October 2009. The two cores were extracted approximately 30 metres apart (Fig. 1C) from a Kawhaw platform. Each record is a combination of a long and a short core. Long cores were collected using a hammer-driven piston corer (Chambers and Cameron 2001). Short cores were collected from the uppermost sediments using a soft sediment piston corer. Each core was sampled at 1 cm intervals for geochemical analysis. Short and long cores were correlated using loss on ignition (LOI) data (ESM1 Fig 2).

Sampling of terrestrial organic matter sources

Plants

Terrestrial plant samples were collected from around the lake from the three major tree taxa in the catchment: *Eucalyptus*, *Banksia*, and Casuarinaceae. Live and dead specimens were taken from each taxon. Live leaf and twig specimens were taken directly from the tree. Dead leaf and twig specimens were taken from twigs (with leaves attached) that had fallen from and were adjacent to their parent trees. The dried leaves collected were not resting on the ground to ensure no microbial degradation had occurred. Samples were separated into three groups within each tree taxon: live leaves, dead leaves, and twigs. All samples were cut up into approximately 1 cm^2 pieces and dried overnight at 100°C. Sub-samples of terrestrial plant specimens were burned at 250°C, 500°C, and 750°C for four hours. Burning of samples was conducted because fire is an important influence on catchment biota, and charcoal can greatly influence sedimentary organic matter characteristics. Sample burning was therefore done to determine if burning (i.e., from forest fires) affects C:N or $\delta^{13}C$ of terrestrial plants. All samples were then ground, and analysed for C:N and $\delta^{13}C$.

Catchment soil organic content

To determine the amount of organic matter in Blue Lake's catchment soils, soil was collected in six catchment transects in May 2019. Each transect had three sample sites: on the bottom of the hill slope, mid-slope, and the top of the slope. At all sites on all transects, surface soil (top 5 cm) and leaf litter (any debris above soil surface) samples were taken. Three transects had 25 cm profiles taken at each site (ESM1 Fig. 4). In each profile five samples covering 5 cm depth were taken. All samples were homogenized, dried, and ignited at 550°C for four hours to estimate organic content (Heiri et al. 2001).

Aquatic plant sampling

In August 2018 a survey was undertaken to map the aquatic habitats in Blue Lake using a combination of an underwater remotely operated vehicle (ROV; Deep Trekker DTG2) and visual survey by snorkelers. The ROV surveyed points around the lake perimeter at approximately 50 m intervals and in the middle of the lake (equidistant between shores) at approximately 100 m intervals (ESM1 Fig. 1). The lake perimeter survey points were 3–4 m from the bank and photographed at a depth of approximately one metre above the sediment surface. The snorkelers surveyed sites immediately adjacent to shore approximately every 200 m around the perimeter of the lake (ESM1 Fig. 1). Both the ROV and snorkelers surveyed one square metre of lake floor to determine the dominant plant species, percent coverage of all plant species, the presence/absence of terrestrial plants (e.g. leaves, stems), and presence/absence of bare sand and mud.

Where present, plant and algal samples from each site were collected for subsequent identification. Algal material was preserved *in situ* with 2% buffered formaldehyde. Sub-samples were mounted on flat slides and observed at 400× magnification. A total of 300 algal units were identified from each sample to the lowest taxonomic rank and results expressed as proportional abundance (Barbour et al. 1999). In order to create a habitat map of the lake, the dominant habitats were interpolated between points using survey data and photos (e.g. Fig. 1D,E,G) to define boundaries of habitats.

Modern sediment, soil and plant and C:N and $\delta^{13}C$

Lake surface sediment, catchment topsoil, plant, and algal samples were collected for TOC, TN, and $\delta^{13}C$ analysis. Samples of topsoil represent the top 3 cm after leaf litter was cleared and were collected in 2017. These samples were taken within 10 m of the lake edge (ESM1 Fig 4). All samples were pre-treated with 5% HCl for 24 hours to remove any calcium carbonate, followed by successive rinses with deionised water. The resultant material was oven dried at 40ºC overnight. The dried material was ground to a powder using a standard freezer milling in liquid nitrogen and loaded into tin capsules for elemental and isotope analysis.

$^{13}C/^{12}C$ of samples were analysed by combustion in a Costech ECS4010 Elemental Analyser and went on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer. Carbon isotope ratio ($\delta^{13}C$) values were calibrated to the VPDB scale using within-run laboratory standards calibrated against NBS-18, NBS-19 and NBS-22. Replicate analysis of well-mixed samples indicated a precision of $\pm$ <0.1‰ (1 SD). Percent carbon and nitrogen concentrations were also measured and calibrated against an internal laboratory standard (SOILA, BROC2). Replicate analysis of well-mixed samples indicated a precision of $\pm$ <0.1.

Sediment chronology

A master stratigraphy for Blue Lake was developed by sequence slotting (Thompson and Clark 1990) the two sediment sequences, collected in May 2007 and October 2009, using loss on ignition-derived organic matter concentration (ESM1 Fig. 2). The performance of this process was evaluated, prior to construction of the age model, using the delta value of Gordon et al. (1988) (ESM Fig. 3) that had an associated correlation coefficient of $R = 0.90$. By combining seven ^{14}C dates and one ^{137}Cs date from the 2007 record (Barr et al. 2013) and 12 new ^{14}C dates from the 2009 core, a master age model was developed (Fig. 2; Table 1). All but two radiocarbon dates were obtained from the humin fraction of the bulk organics in the sediment and were calibrated using SHCal13 (Hogg et al. 2013) in the 'rBacon' package (Blaauw and Christen 2011) in R (R Core Team 2020). The two remaining radiocarbon dates were obtained from macrofossils collected from the sediment. Accumulation rate mean and 95% confidence intervals were calculated and plotted against time in the 'rBacon' package (Blaauw and Christen 2011) after creation of the age model.

Data analysis techniques

Previously published diatom and pollen data from the 2007 record (Barr et al. 2013) were analysed using detrended correspondence analysis (DCA) using the 'vegan' package v.2.5-6 (Oksanen et al. 2019) in R (R Core Team 2020). Stratigraphically constrained cluster analysis (CONISS) (Grimm 1987) in the 'rioja' package v.0.9-21 (Juggins 2017) was used to determine zonation of the core $\delta^{13}C$, C:N, TN, TOC, and percent organic (LOI) data (ESM1 Fig. 5). A broken stick test in the 'PCDimension' package (Wang et al. 2018) was used to determine the ideal number of groups.

Results

Lake habitats

The main aquatic plant species in Blue Lake are the emergent macrophyte *Lepironia articulata* and the submerged macrophyte *Eleocharis difformis* (Fig. 1C,F). *L. articulata* grows at depths < 5.5 m and *E. difformis* grows at depths > 0.5 m (Fig. 1C). *L. articulata* grows mostly along the fringes of the lake and *E. difformis* grows both in the deep centre (~10 metres) of the lake and along the fringes. Other aquatic macrophytes found in the lake are: *Cycnogeton* sp., *Myriophyllum* sp., and *Gahnia* sp. Most of the deep and interior portions of the lake are bare mud (Fig. 1D). One patch of bare sand is located along the southern shore of the south arm (Fig. 1C). Terrestrial plant material was found in patches along the fringes of the lake, usually within two metres of the shore (Fig. 1E). This debris included bark, leaves, branches, and twigs.

Algal mats and biofilms cover many lake habitats, although they are most abundant in the southern arm (Fig. 1C). Algal assemblages in Blue Lake are dominated by two macrophytic cyanobacterial species: *Symphyonema karboorum* G.B.McGregor and *Hapalosiphon pumilus* Kirchner ex Bornet & Flahault. Less abundant communities of the cyanobacterium *Scytonema mirabile* Bornet are found throughout the lake as well (ESM1 Table 2). Generally, *H. pumilus* and *S. mirabile* are found in benthic habitats (McGregor 2012). Large clumps or 'balls' of *H. pumilus* are found on bare mud in the centre and in parts of the northern arm of the lake.

Modern plant, algae, and soil elemental concentration and isotope data

Plants were divided into groups based on their habitat (terrestrial, aquatic macrophyte, and algae). Group averages are plotted in Figure 3 with all data shown in ESM1 Table 3. Burned terrestrial samples fall in the same δ^{13}C range as terrestrial plants (–33‰ > δ^{13}C < –27‰; mean = –30 ± 1.3‰) but have a much larger range of C:N values (31 > C:N < 2336; mean 254 ± 388), although only two samples have C:N >1000 (*Eucalyptus* and Casuarinaceae sticks burned at 750°C). All terrestrial (mean δ^{13}C = –30 ± 1.2‰, mean C:N = 127 ± 120, n = 13) and aquatic plant (mean δ^{13}C = –27 ± 2.1‰, mean C:N = 62 ± 43, n = 10) samples fall in the δ^{13}C and C:N range typical for C_3 plants (–33‰ > δ^{13}C < –22‰, C:N > 15; Fig. 3, ESM1 Table 2, 3). Benthic algal δ^{13}C (mean –31 ± 3.6‰) is generally lower than terrestrial plants or aquatic macrophytes and falls partially outside the C_3 range (–38‰ > $\delta^{13}C_{algae}$ < –25‰; mean δ^{13}C = –31 ± 3.6‰). Algal C:N ranges from 15 – 50 (mean 20 ± 7.7) and falls within the range for C_3 plants (ESM1 Table 2) (Meyers and Teranes 2002).

The catchment soils of Blue Lake have organic content (LOI_{org}) of <5%, which is highest in the uppermost 5 cm of soil and rapidly falls to zero at 25 cm (ESM1 Fig. 4; ESM1 Table 5). LOI_{org} of leaf litter (mean 50%) was much higher than catchment soils (ESM1 Fig. 4). Mean δ^{13}C and C:N values of catchment soils are –28.5‰ and 67.3, respectively (ESM1 Table 1, 3).

Sediment chronology

The age model based on a composite of the two sediment sequences exhibits a predictable increasing age with depth, and a basal age of 7.5 cal kyr BP (Fig. 2; Table 1). The age model consists of seventeen ^{14}C dates and one age derived from the first appearance of ^{137}Cs (dated to -5 cal yr BP; Table 1) (Barr et al. 2013). A Bacon age model was initially run with all 20 dates (Table 1). However, two clear outliers were removed from subsequent iterations (OZY201, OZY202; Table 1). These two ages are much older than other samples of a similar depth.

Plant macrofossils that were identified as *Elecharis difformis* were dated (OZY206, OZY207; Table 1). These plant macrofossils returned ages approximately 1000 years younger than the radiocarbon age of the bulk organics in the sediment (OZY198, OZY199; Table 1) in which they were found. The deeper macrofossil (OZY207) and its paired bulk organics (OZY199) from the 2009 core were compared to a sample from the 2007 core (Wk30239) of the same master depth. The radiocarbon ages of the two bulk organic samples correspond well (~70 years difference). This indicates that either the plant was reworked in the sediment sequence, or that bulk organic ages from both cores may be subject to a systematic offset. The similarity in offset of the two macrofossil samples and surrounding bulk sediment organics suggests the latter. Unfortunately, the small number of macrofossil samples makes it difficult to determine if the 1000-year offset is persistent throughout the record. Therefore, no corrections for a possible reservoir effect was applied. Groundwater ages from the aquifer that is the source of Blue Lake water are generally quite young (<100 years) (Hofmann et al. 2020) and sediment carbonate concentrations are low (Barr et al. 2013), reducing the likelihood that the offsets between the radiocarbon ages are derived from hardwater reservoir effects.

Sediment organic matter TOC, C:N, and $\delta^{13}C$ data

The sediments of Blue Lake consist of homogenous, fine grained, dark organic sediments (Barr et al. 2013). Total organic carbon is lowest (4.8%) in the sediments aged approximately 4.5 cal kyr BP (Fig. 4B). Stratigraphically constrained cluster analysis (CONISS) (Grimm 1987) of core geochemical data showed four distinct phases: 7.5 – 6.5 cal kyr BP (phase 1), 6.5 – 4.2 cal kyr BP (phase 2), 4.2 – 1.8 cal kyr BP (phase 3), 1.8 – 0 cal kyr BP (phase 4) (Fig. 4; ESM1 Fig. 5). The highest TOC values occur at approximately 4 cal kyr BP (16.8% TOC) in phase 3. TOC is relatively low from 7.5 cal kyr BP to 4 cal kyr BP (average 7.8%; phases 1 and 2), and relatively high from 4 cal kyr BP to 0 cal kyr BP (average

9.2%; phases 3 and 4). C:N values range from 15 to 32, with the lowest value occurring in the uppermost sediments (0 cal kyr BP; phase 4) and the highest occurring at 4.7 cal kyr BP in phase 2. Notable C:N excursions occur at approximately 4.4 cal kyr BP and 4.2 cal kyr BP in phase 2, with C:N decreasing by ~10 during each these excursions. C:N ratios prior to these events tend to be higher (>25) than average, while C:N values after these excursions are lower (<20) than average. Sedimentary $\delta^{13}C$ ranges from –29.3‰ to –35.2‰. These $\delta^{13}C$ values fall generally in the C_3 plant range (Meyers and Teranes 2002). The largest change in the record is a rapid decrease in $\delta^{13}C$ of approximately 5‰ that occurs at 4.2 cal kyr BP, during the transition from phase 2 to 3. Another large trough in $\delta^{13}C$ occurs at approximately 1.2 cal kyr BP (phase 4), where the $\delta^{13}C$ reaches its lowest values in the record of –35.2‰.

Discussion

Sources of organic matter in Blue Lake

C:N ratios of lacustrine algae on North Stradbroke Island are much higher than generally observed elsewhere (Cadd et al. 2018), with the C:N of modern algae from Blue Lake averaging ~20 (ESM1 Table 2). Cadd et al. (2018) have attributed high C:N values in lacustrine algae on North Stradbroke Island to nitrogen limitation, consistent with other observations of severe nitrogen limitation producing algal C:N >15 (Healey and Hendzel 1980; Hecky et al. 1993; Talbot and Lærdal 2000). Previous studies on lake sediments in south-eastern Queensland interpret sediment C:N values >11 as being indicative of terrestrial sources of organic matter (Barr et al. 2013; Barr et al. 2017; Hembrow et al. 2014; Hembrow et al. 2018). However, our data, and those in Cadd et al. (2018), indicate that the presence of algae and aquatic macrophytes with higher C:N ratios suggest that terrestrial material may not have been the dominant source of organic matter in dune lake sediments.

The low concentration of carbon in Blue Lake's sand-dominated catchment soils (ESM1 Fig. 4; ESM1 Table 5; avg ~5%) (Fig. 1C), high catchment soil permeability (Leach 2011), and an absence of permanent inflow streams indicates there is likely to be little overland transport of terrestrial organic material into Blue Lake. Indeed, the C:N values of terrestrial soil, plant material, and charcoal (means 67, 126, and 247 respectively; ESM1 Table 3) imply that if substantial input of terrestrial material had occurred, higher values of sedimentary organic matter C:N would result. Furthermore, observations in the field showed that very little terrestrial material was found in the lake, especially around the core site (Fig. 1C). Hence, terrestrial material is most likely a small contributor to lake sedimentary organic matter and the dominant source of sediment organic matter in Blue Lake throughout its history is autochthonous. This finding is important because it means that the sedimentary $\delta^{13}C$ record from Blue Lake can primarily be interpreted as reflecting changes in lake productivity. Furthermore, it suggests that past interpretations of a terrestrial sediment organic matter source in Blue Lake (Barr et al. 2013) and other large sand island lakes (Atahan et al. 2015; Hembrow et al. 2014; Hembrow et al. 2018) may need to be revisited.

Conceptual framework of ecological change in Blue Lake

Given the low nutrient concentrations observed in many sand island lakes (Moss 2017), including Blue Lake (Barr et al. 2013), it is important to know the sources of nutrients in those lakes. Understanding nutrient dynamics in Blue Lake is imperative to interpreting the growth of algae and aquatic macrophytes through time, and to elucidate the evolution of the lake. With little terrestrial input, the three main sources controlling the input of nutrients into the lake are: lake sediments, the atmosphere, and groundwater.

Lake sediments are often the largest reservoir and most important source of nutrients in lakes, especially in oligotrophic systems (Vadeboncoeur and Steinman 2002). Aquatic macrophytes and benthic algae often utilise this reservoir with little reliance on water column nutrients (Périllon and Hilt 2016, 2019). In Blue Lake, it was observed (Fig. 1D,E,G) that most algae grow epiphytically on aquatic macrophytes as has previously been noted (McGregor 2012, 2018). Therefore, epiphytic algae have little interaction with lake sediments. This is likely to mean that epiphytic algae and aquatic macrophytes source their nutrients, respectively, from the water column and lake sediments. Hence, water column nutrients are likely to exert a much stronger control on algal concentrations than aquatic macrophyte abundance in Blue Lake. In addition, since lake sediments represent a relatively unchanging pool of nutrients, cycling of nutrients between the sediments and macrophytes, which "return" nutrients to the sediment after death (Søndergaard et al. 2003; Horppila and Nurminen 2003), any changes in the balance of organic matter sources most likely come from algae.

Due to the high permeability of sand island soils (Leach 2011), water column nutrients are most likely sourced through groundwater and not through in-wash of terrestrial plants or soil. Water column nutrient and lake discharge data from Blue Lake between 1996 and 2002 (Barr et al. 2013) indicate a link between groundwater inputs and water column nutrient concentrations (ESM1 Fig. 6). Lake water residence time and water column nutrient concentrations are positively correlated. Annual average nitrogen concentration vs. residence time has an $r = 0.75$, $p < 0.05$, while annual average phosphorus vs. residence time has an $r = 0.68$ ($p < 0.1$; $n = 7$; ESM1 Fig. 6). Hence, at annual time scales, approximately half the water column nutrient concentration variation can be explained by changes in lake water residence time. Therefore, water residence time is an important control on nitrogen in Blue Lake, with high residence times related to high nitrogen concentrations, and low residence times related to low nitrogen concentrations (ESM1 Fig. 6).

Water column nitrogen concentrations may also be increased through fixation by cyanobacteria (Liu et al. 2019) and low nutrient concentrations in the water column tend to increase nitrogen fixation by cyanobacteria in oligotrophic lakes (Liu et al. 2019; Brauer et al. 2012). The low nutrient concentrations in sand island waters and soils may therefore tend to favour cyanobacterial nitrogen fixation in Blue Lake. However, water column nutrient data from Blue Lake showed sustained nitrogen depletion over several years (Barr et al. 2013), and a prior survey of sand island lake and wetland algae found that diatoms and other chlorophytes dominate the planktonic microflora (McGregor 2012). Therefore, proportionally low cyanobacterial composition (Fig. 1C), coupled with low lake nitrogen levels, suggests cyanobacterial nitrogen fixation may only represent a small part of Blue Lake**'s** water column nitrogen budget.

The relationship between residence time and phosphorous may be driven by temperature and sediment-water interactions. Temperature is a major driver of phosphorus transport from sediments into the water column, with higher temperatures generally leading to more mobilisation (da Silva et al. 2020; Dadi et al. 2020; Liu et al. 2018). Average air temperatures at Blue Lake are generally >15°C year round (Bureau of Meteorology 2020), which tends to promote phosphorus mobilisation into the water column throughout the year. Water residence time may influence phosphorus concentrations by causing the export of mobilised phosphorus through the stream outflow when residence time is low. By contrast, high residence time allows phosphorus mobilised from the lake sediments to accumulate in the water column, therefore increasing phosphorus concentrations. However, it must be noted that phosphorous levels in the water column are quite low (mean 4 mg m^{-3}) (Barr et al. 2013), indicating phosphorous has most likely been scarce in Blue Lake through time.

Water residence time in Blue Lake is strongly linked to precipitation through recharging of the regional aquifer on North Stradbroke Island (Hofmann et al. 2020). Rainfall and nutrients, in turn, have important impacts on the algae of Blue Lake that can be recorded in the C:N and $\delta^{13}C$ of sediment organic matter. Hence, changes in these components of sediment organic matter may elucidate long term changes in precipitation on North Stradbroke Island. Given the relationship between residence time and nutrient concentrations in Blue Lake, we hypothesise that, on decadal to centennial timescales, nutrient concentrations in the lake are controlled by precipitation via its influence on lake residence time. Hence, increases in C:N and $\delta^{13}C$ are indicative of low algal biomass, driven by low nutrient concentrations and decreased residence time of lake water due to higher rainfall. Conversely, lower C:N and $\delta^{13}C$ indicate higher algal biomass, driven by higher nutrient concentrations and an increase in the residence time of lake water due to lower rainfall.

Precipitation and nutrient driven changes in Blue Lake sediment organic matter through time

The Blue Lake sediment record is split into four phases, defined by a CONISS analysis of the geochemical data (ESM1 Fig. 5), which are discussed individually below.

Phase 1 (7.5 cal kyr BP – 6.5 cal kyr BP)

High TOC, C:N, and low $\delta^{13}C$ values indicate a low algal abundance that declines through phase 1 (Fig. 4B,C,D). The diatom taxon *Cymbella* aff. *falaisensis* is found at its highest relative abundances in this phase (Barr et al. 2013), and is associated with high oxygen content and low nitrogen concentrations in the water column (Van Dam et al. 1994). High relative abundances of *Cymbella* aff. *falaisensis*, therefore, support our interpretation of low benthic algal biomass in this phase.

The mid-Holocene was wetter than present in the Australian subtropics (Donders et al. 2007; Petherick et al. 2013; Reeves et al. 2013) and this is evident in the rainfall reconstruction from Swallow Lagoon on North Stradbroke Island (Fig. 4H). In this context, higher precipitation on the island likely resulted in shorter water residence times in Blue Lake which, in turn, resulted in low nutrient concentrations in the water column and low algal biomass (Fig. 4C,D).

Phase 2 (6.5 cal kyr BP – 4.2 cal kyr BP)

Low TOC, with high C:N and $\delta^{13}C$ indicate low benthic algal biomass through phase 2 (Fig. 4B,C,D). C:N and $\delta^{13}C$ values reach their highest values in the record (32 and –29.5‰, respectively) which indicate the minimum algal biomass for the record. A large trough in $\delta^{13}C$ between 5.5 cal kyr BP and 5.2 cal kyr BP may be related to a short period of high primary productivity (Fig. 4D). The short-lived decline in $\delta^{13}C$ is most likely related to productivity, because the C:N data do not show an equivalent reduction, as would be expected if there was a change in the source of organic matter. This phase of elevated algal productivity may be related to the relatively dry climates inferred from the Swallow Lagoon record from 6 cal kyr BP to 5.2 cal kyr BP (Barr et al. 2019) (Fig. 4H).

Phase 3 (4.2 cal kyr BP – 1.8 cal kyr BP)

The largest shift in the record occurs at 4.2 cal kyr BP and is indicated by marked declines in C:N and $\delta^{13}C$ that are immediately followed by an increase in TOC (Fig. 3, 4B,C,D; ESM1 Table 2, 3). This shift is also accompanied by an increase in the sediment accumulation rate (Fig. 4A). An increase in the magnitude El Niño phases (Barr et al. 2019) may have produced more droughts and longer lake water residence times, increasing nutrient concentrations and algal biomass. In combination these factors explain the long term decline in sedimentary C:N through phase 3 (Fig. 4C).

Diatoms also exhibit the largest change in species assemblages at ~4.1 cal kyr BP (Fig. 4F), and pollen data indicate a substantial environmental change toward drier conditions at this time, with a decrease in sclerophyll arboreal taxa (Barr et al. 2013). The reduction in sclerophyll taxa is related to a transition toward more drought-resistant Casuarinaceae (Barr et al. 2013), which suggest a short, dry period at approximately 4 cal kyr BP. A shift toward dry conditions is further supported by a decrease in charcoal (Fig. 4E) (Barr et al. 2013), which is inferred to have been caused by a transition toward more open forests on North Stradbroke Island (Mariani et al. 2019).

A short increase in $\delta^{13}C$ at approximately 3.6 cal kyr BP and a spike in TOC from 4.2 cal kyr BP to 3.6 cal kyr BP indicates an increase in lake productivity. Diatom data imply an increase in nutrients (Barr et al. 2013) at the phase 2 to 3 transition, which could be related to a drying trend evident at Swallow Lagoon (Barr et al. 2013; Mariani et al. 2019) (Fig. 4H; ESM1). The diatom DCA indicates a response to the drying seen at Swallow Lagoon at 3.2 cal kyr BP, with a large excursion between 3.4 and 3.1 cal kyr BP. Relatively stable geochemical and pollen data through the rest of the phase suggest an unchanging catchment and lake environment, with high algal abundance.

We interpret these changes to be related to an increase in El Niño-like phases, as observed in nearby Swallow Lagoon. A change from a wet to a dry climate on North Stradbroke Island at approximately 3.2 cal kyr BP (Barr et al. 2019) (Fig. 4H) is supported by pollen and charcoal records that show a transition to drier climate at 3.4 cal kyr BP (Mariani et al. 2019). The discrepancy between the timing of the Blue Lake shift (4.2 cal kyr BP) and the shift in climate seen in Swallow Lagoon may be related to uncertainties in the Blue Lake age model. If the ~1000-year age-offset between the paired macrofossil and bulk sediment radiocarbon ages was used to correct the older sediment ages, the change in the data from Blue Lake would overlap with the change in rainfall inferred from Swallow Lagoon. This, in turn, would modify the timing of events interpreted from the Blue Lake organic matter data, but does not change the overall conclusions regarding the drivers of these changes.

Phase 4 (1.8 cal kyr BP to 0 cal kyr BP)

A decrease in $\delta^{13}C$ at approximately 1.5 cal kyr BP coincides with the lowest sediment accumulation rate in the record (Fig. 4A,D). The $\delta^{13}C$ data suggest continued high algal biomass, but the drop in accumulation rates may imply lowered productivity (Fig. 4A). Precipitation is inferred to be relatively high at this time (Barr et al. 2019) (Fig. 4H), which would lead to higher throughflow and lower nutrient concentrations in the water column, reducing productivity. A short increase, followed by large negative excursions in $\delta^{13}C$ and TOC around 1 cal kyr BP indicates higher productivity, which is supported by higher accumulation rates (Fig. 4A,B,C). A change in diatom and pollen DCA at approximately 1 cal kyr BP also suggests a shift in lake conditions, possibly related to a reduction in precipitation (Fig. 4F,G).

Little variability in the Blue Lake organic matter record is observed through the Little Ice Age (500 to 100 yr. BP) (Rustic et al. 2015) and the period of European colonisation. A minor reduction in $\delta^{13}C$ of ~1.5‰ occurred, with a small increase (2–3) in C:N at ~400 yr. BP. Consistently higher rainfall on North Stradbroke Island occurred during the Little Ice Age (Barr et al. 2019), but low climate variability inferred from lake (Barr et al. 2014) and tree ring (Cook et al. 2000) records in Australia may explain why there is little response from Blue Lake during this time. A large reduction in TOC occurred at approximately 0 yr. BP. This shift may be related to a decrease in precipitation at approximately the same time on North Stradbroke Island (Barr et al. 2019) (Fig. 4H).

The sensitivity of Blue Lake to climate

A previous study of the history of Blue Lake suggested that water quality and hydrology were stable since the mid-Holocene (7.5 kyr BP), due to largely constant groundwater throughflow (Barr et al. 2013). This study has shown that Blue Lake is, in fact, sensitive to changes in climate at centennial to millennial scales. New modern C:N and $\delta^{13}C$ data indicate that autochthonous, rather than allochthonous, material was the dominant source of organic matter for the last 7,500 years. This demonstrates that changes in sedimentary C:N and $\delta^{13}C$ in Blue Lake are not mediated by catchment processes, but are instead related to climate. Climate control manifests itself through strong influence of water residence time on the internal nutrient dynamics of Blue Lake. Given the projected increase in temperatures and reduction in rainfall over south-east Queensland (King et al. 2017; Grose et al. 2020), lower groundwater inflow into, and higher residence times in, Blue Lake may be expected. This, in turn, would lead to higher algal biomass in Blue Lake and similar lake systems. This conclusion contrasts somewhat with Barr et al. (2013) who placed less emphasis on the future risk of climate change on Blue Lake. It also highlights the need to link spatially explicit climate model outputs (i.e. downscaled projections) to realistic hydrological models of Blue Lake and other lakes to simulate their future.

Conclusions

We have re-interpreted the evolution of Blue Lake, North Stradbroke Island, through a survey of modern plants, algae and soils and a new, high-resolution multiproxy organic matter record. We have shown that in this lacustrine system, algae do not fit the traditional C:N interpretation of sedimentary organic matter sources. This reinterpretation of sediment organic matter leads to the conclusion that Blue Lake is more climatically sensitive than previously thought. Changes in Blue Lake nutrient concentrations are controlled by precipitation impacts on groundwater flow and lake residence time. Our new core data indicate there was a transition to higher nutrient concentrations (although the lake is still oligotrophic), driven by a decrease in precipitation, favouring algal growth in Blue Lake around 4.2 cal kyr BP. The change may have been driven by a decrease in rainfall related to a shift in millennial-scale ENSO mean state and, or, more frequent El Niño events, but age model uncertainty makes drawing a decisive conclusion difficult. This study highlights the importance of the combined use of contemporary and palaeoenvironmental data when exploring how lake systems respond to climate over long timescales. C:N and $\delta^{13}C$ can be ambiguous palaeoclimate proxies due to multiple drivers, so it is useful to assess them in the context of other information. This is now being undertaken using Fourier transform infrared spectroscopy (Maxson et al. 2021). Better understanding of the source and sedimentation of organic matter in lakes allows for a stronger foundation for inferences about lake behaviour.

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Table 1

All ages collected from both cores. Ages denoted with * were not used in the final age model. † denotes a ^{137}Cs date from Barr et al. (2013). Bolded ages were previously published in Barr et al. (2013). Sediment basal age previously published in Tibby et al. (2017). Calibrated ages reported the mean age of the calibrated age range.

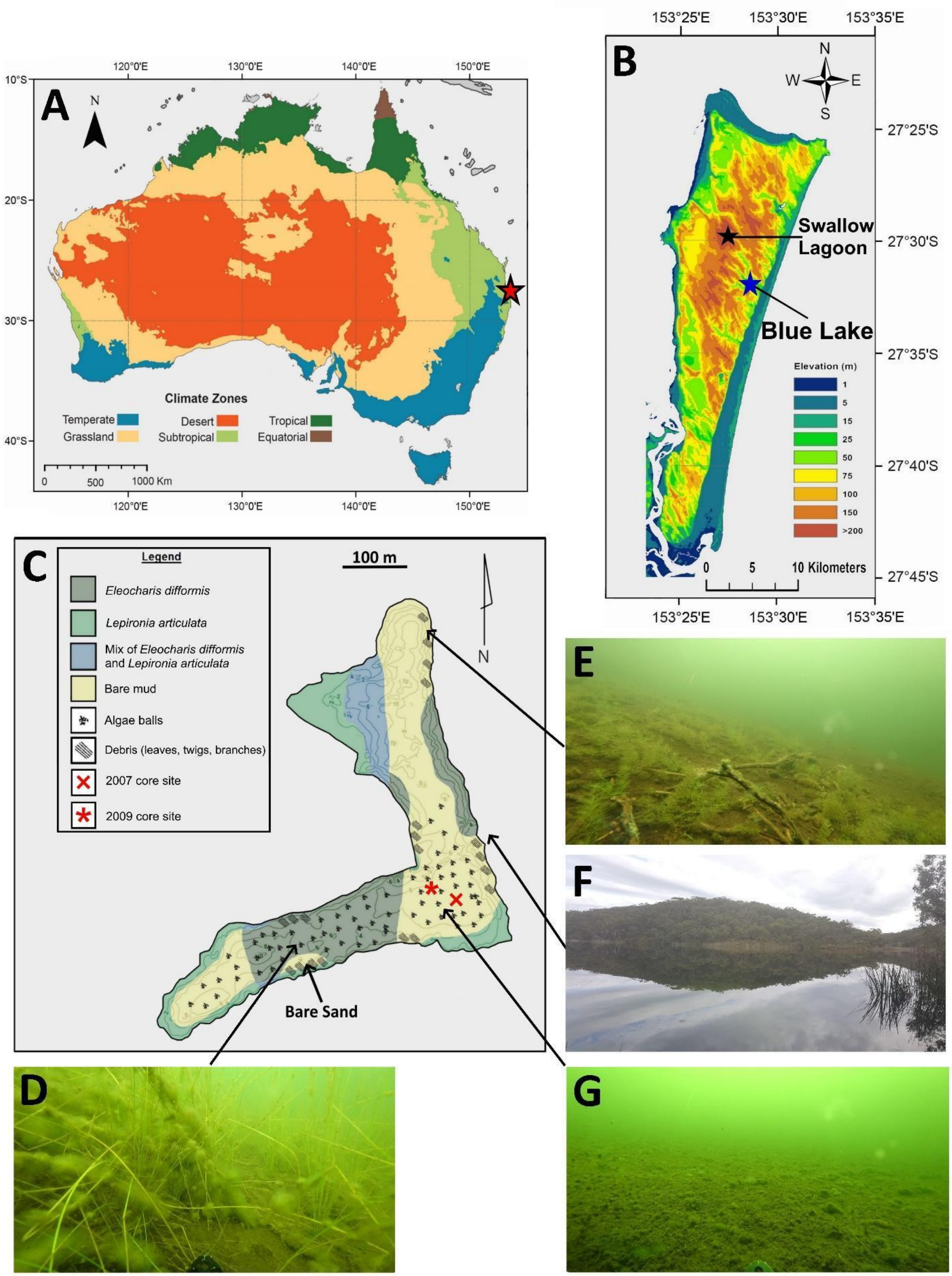
All core ages								
Core	Sample type	Sample ID	Lab Code	Composite depth	$\delta^{13}C$ (‰)	^{14}C age (yr BP)	Mean calibrated age (cal yr BP)	Calibrated age range (cal yr BP)
2007	Sediment	STD 8		8			**-5†**	
2009	Sediment	BLP-2 5	OZY194	19.317	-29.3	1110±20	953	919 - 1033
2009	Sediment	BLP-2 15	OZY195	36.176	-32	1610±25	1464	1383 - 1523
2007	Sediment	BL07 46	OZY196	46	-27.5	2445±20	2382	2346 - 2445
2007	Sediment	STD 10	Wk30238	50		2397±30	**2432**	2367 - 2568
2009	Sediment	BL09 32	OZY198	91.405	-30.4	3135±25	3313	3223 - 3385
2009	Plant	BL09 32p	OZY206	91.405 plant	-29.8	2290±25	2260	2190 - 2331
2009	Sediment	BL09 65	OZY199	109.153	-30	3885±25	4134	4020 - 4204
2009	Plant	BL09 65p	OZY207	109.153 plant	-30.8	3005±25	3118	3001 - 3236
2007	Sediment	STD 70	Wk30239	110		3807±30	**4158**	4030 - 4228
2009	Sediment	BL09 97	OZY200	137.907	-27.8	3975±25	4462	4359 - 4539
2009	Sediment	BL09 130	OZY201	142.49	-29.7	6385±30	7275*	7170 - 7331
2009	Sediment	BL09 162	OZY202	147.156	-28.2	5325±25	6073*	5986 - 6181
2007	Sediment	BL07 151	OZY197	151	-30.1	5180±30	5898	5857 - 5947
2009	Sediment	BL09 194	OZY203	152.412	-27.1	4360±25	5277	5183 - 5431
2009	Sediment	BL09 227	OZY204	154.484	-27.2	4675±25	5459	5390 - 5565
2009	Sediment	BL09 250	OZY205	155.1	-27	4875±30	5509	5444 - 5602
2007	Sediment	STD 120	Wk21707	161.5		5111±37	**5790**	5674 - 5894
2007	Sediment	STD 145	Wk22011	182.5		5781±108	**6424**	6258 - 6609
2007	Sediment	STD 195	Wk21708	236.5		6494±40	**7364**	7275 - 7434
	Sediment	BLK2 Base		N/A	-26.3	8530±50	9499	9422 - 9546

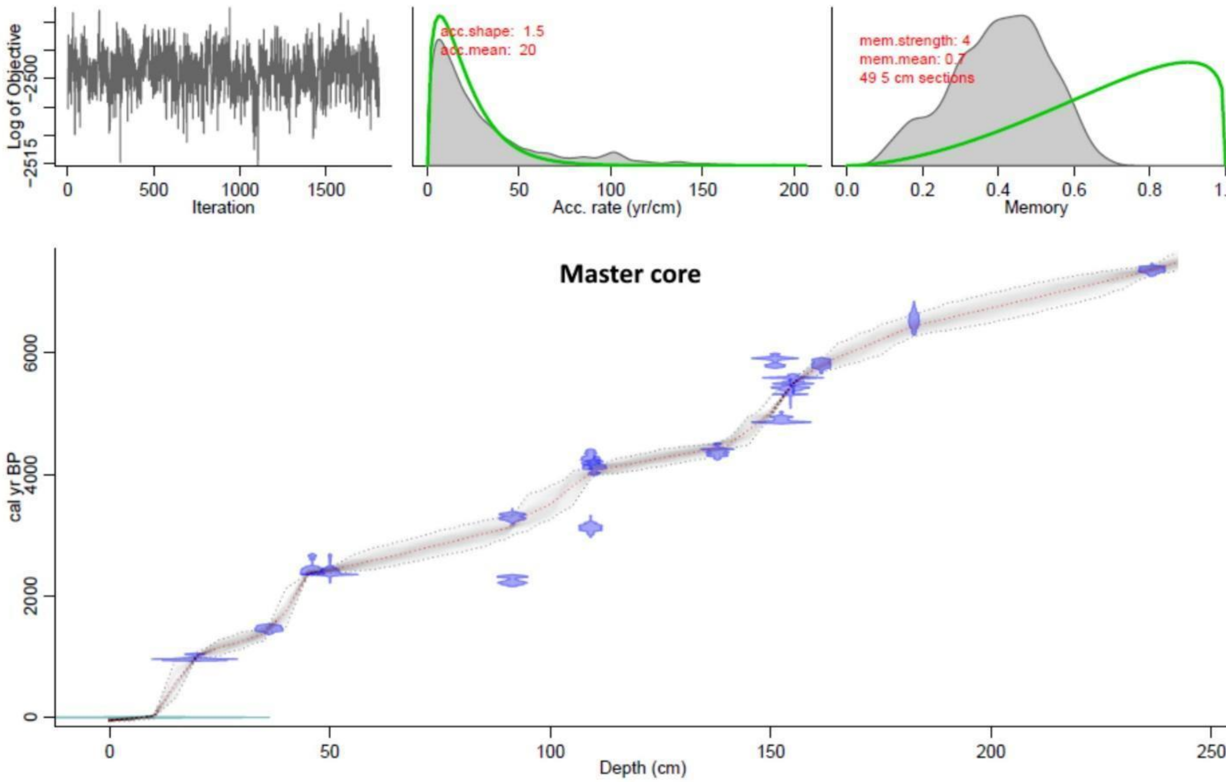
Figure 1: (A) Australian rainfall zones with location of North Stradbroke Island. (B) Elevation profile of North Stradbroke Island with location of Blue Lake (blue star) and Swallow Lagoon (black star). (C) Map of aquatic habitats in Blue Lake. Survey photos from the southern arm (D), northern arm (E), a view of the lake and catchment from the eastern bank (F), and near the core site (G). Data sources (Bureau of Meteorology 2020).

Figure 2: Final age model for master core. See ESM1 for sequence slotting methods and results.

Figure 3: C:N and $\delta^{13}C$ data of Blue Lake core, plants, and phytoplankton. Group averages for plants and phytoplankton are used for defining the signal for each group. Core data coloured by phase. Red rectangle in (A) indicates the area expanded in (B).

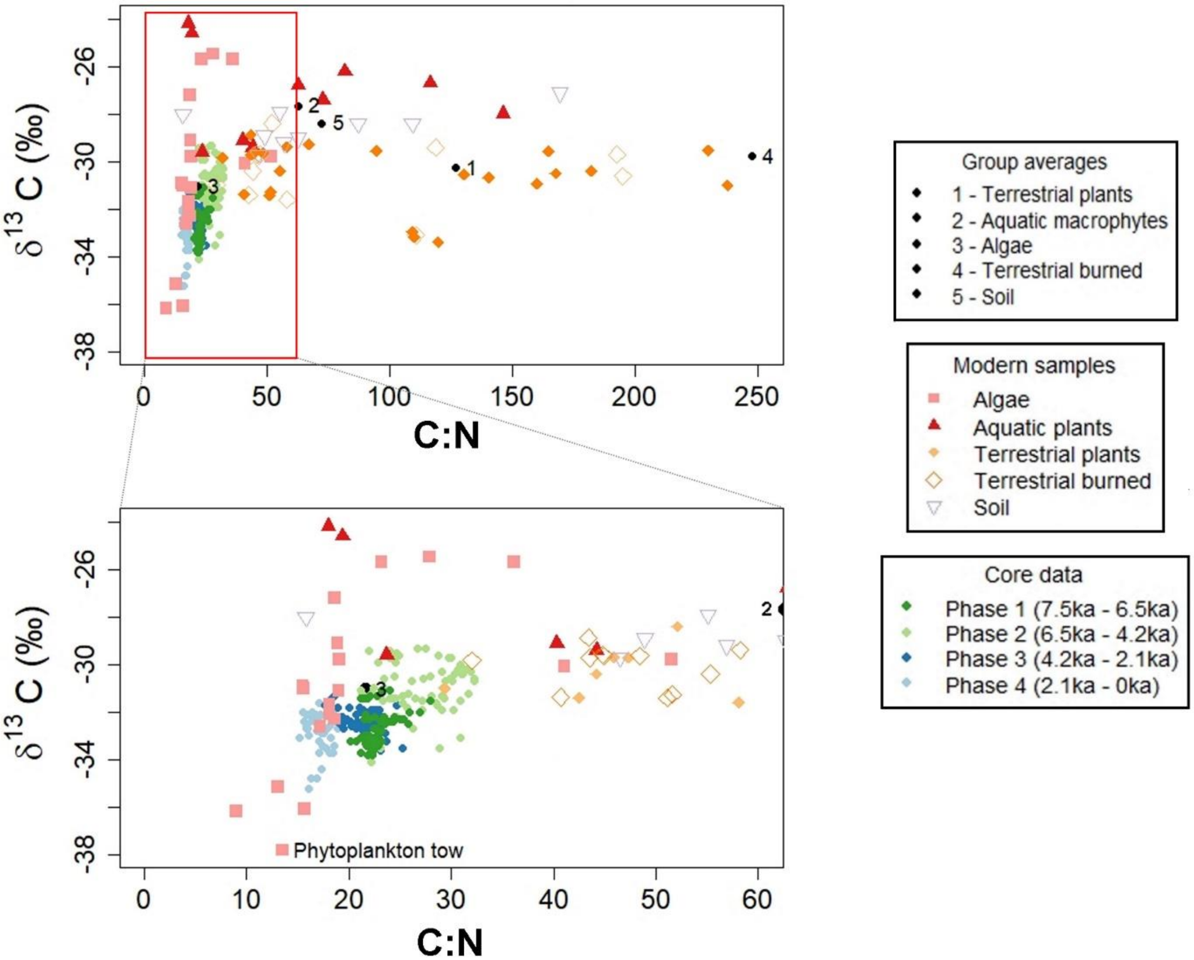
Figure 4: Core data from Blue Lake with phases based on CONISS analysis of $\delta^{13}C$, C:N, TOC, and loss on ignition (ESM1 Fig. 5). (A) Sediment accumulation rate (mean in red, 95% intervals in grey). (B) TOC, (C) C:N, and (D) $\delta^{13}C$ with (E) charcoal concentrations, (F) diatom and (G) pollen data (Barr et al. 2013) DCA axis 1 from Blue Lake. (H) Swallow Lagoon annual rainfall reconstruction (black) derived from carbon isotope discrimination in *Melaleuca quinquenervia* leaves (Tibby et al. 2016) and Generalised Additive Model (orange) (Barr et al. 2019).


A
N
Climate Zones
Temperate
Grassland
Desert
Subtropical
Tropical
Equatorial
0
500
1000 Km
120°0'E
130°0'E
140°0'E
150°0'E
10°S
20°S
30°S
40°S
B
153°25'E
153°30'E
153°35'E
27°25'S
27°30'S
27°35'S
27°40'S
27°45'S
N
W
E
S
Swallow Lagoon
Blue Lake
Elevation (m)
1
5
15
25
50
75
100
150
>200
0
5
10 Kilometers
C
Legend
Eleocharis difformis
Lepironia articulata
Mix of Eleocharis difformis and Lepironia articulata
Bare mud
Algae balls
Debris (leaves, twigs, branches)
2007 core site
2009 core site
100 m
N
Bare Sand
D
E
F
G

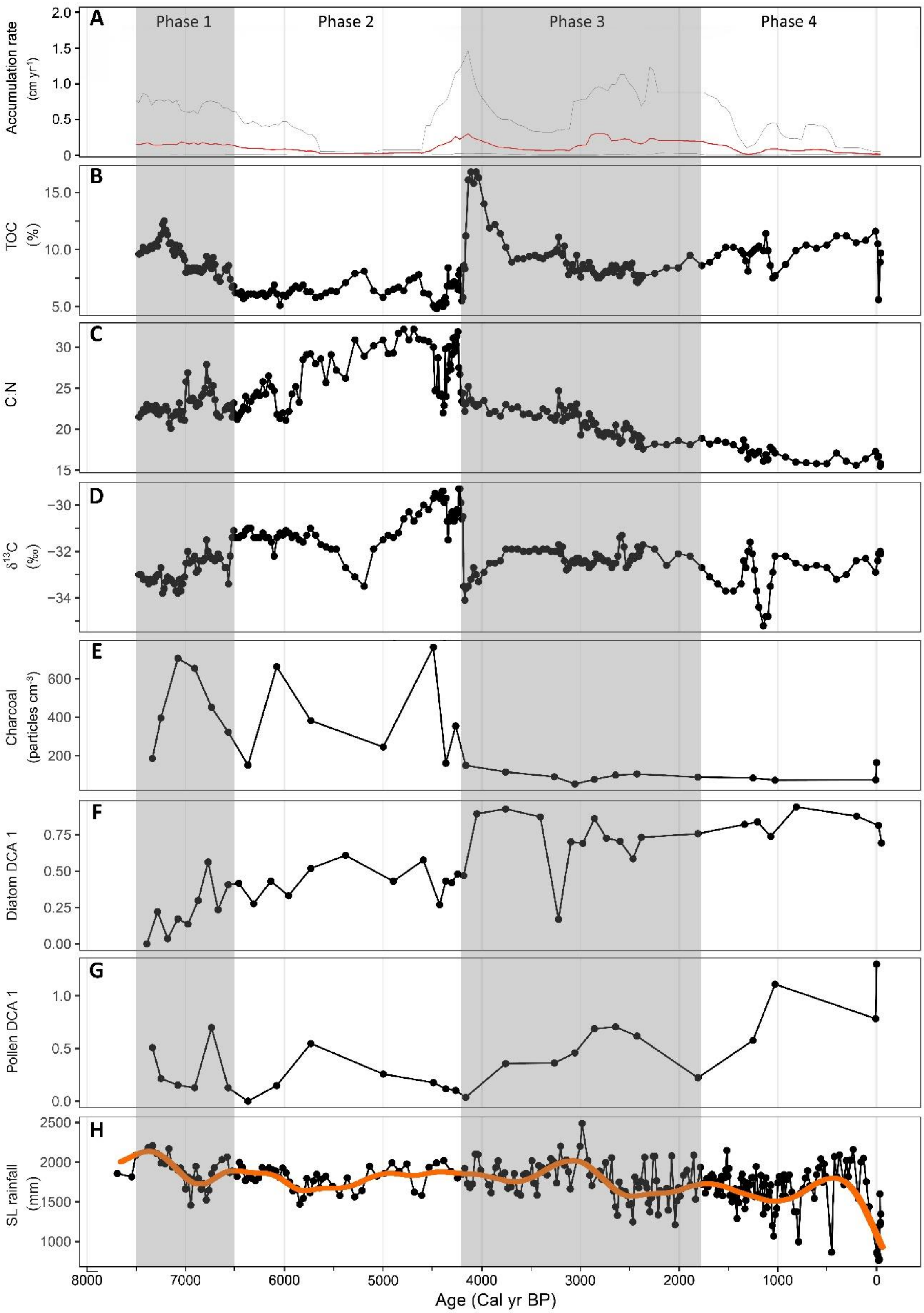


Log of Objective
-2500
-2515
0
500
1000
1500
Iteration
acc.shape: 1.5
acc.mean: 20
0
50
100
150
200
Acc. rate (yr/cm)
mem.strength: 4
mem.mean: 0.7
49 5 cm sections
0.0
0.2
0.4
0.6
0.8
1.0
Memory
Master core
cal yr BP
0
2000
4000
6000
0
50
100
150
200
250
Depth (cm)

926


δ13 C (‰)
C:N
Group averages
1 - Terrestrial plants
2 - Aquatic macrophytes
3 - Algae
4 - Terrestrial burned
5 - Soil
Modern samples
Algae
Aquatic plants
Terrestrial plants
Terrestrial burned
Soil
Core data
Phase 1 (7.5ka - 6.5ka)
Phase 2 (6.5ka - 4.2ka)
Phase 3 (4.2ka - 2.1ka)
Phase 4 (2.1ka - 0ka)
Phytoplankton tow

927



A
Phase 1
Phase 2
Phase 3
Phase 4
Accumulation rate (cm yr⁻¹)
B
TOC (%)
C
C:N
D
δ13C (‰)
E
Charcoal (particles cm⁻³)
F
Diatom DCA 1
G
Pollen DCA 1
H
SL rainfall (mm)
Age (Cal yr BP)

Supplementary Information.

Core correlation and sequence slotting

Methods

Two records were recovered from Blue Lake, one in May 2007 (this paper; Barr et al. 2013) and one in October 2009. The two records were extracted approximately 30 metres apart. Each record is a combination of a long and a short core. Long cores were collected using a hammer-driven piston corer (Chambers and Cameron 2001). Short cores were collected from the uppermost sediments using a soft sediment piston corer. Each core was sampled at 1 cm intervals and organic content was estimated via loss on ignition (LOI) analysis by burning at 550°C for four hours (Heiri et al. 2001; Dean 1974). Short and long cores were correlated using LOI data, resulting in composite records of 242 cm (2007) and 256 cm (2009) (Fig S1).

Trends in the LOI of each composite record suggested that the records were well correlated (Fig S2). LOI data from the cores were sequence slotted (Thompson and Clark 1990) using CPLSlot v3.1b (Hounslow and Clark 2016). An initial slotting using no constraints was used to test how the sequences fit together. A maximum of three constraints were used to minimise overfitting (Fig S3). The constraints were based on clear trends within the LOI data and initial slotting results. The quality of fit was evaluated using the delta value of (Gordon et al. 1988) prior to construction of the age model.

Results

Initial slotting with no constraints yielded a sequence that suggested the 2009 core sequence fit completely into the 2007 core. This finding is in agreement with the basal ages of each core, with the 2009 core yielding an age 2 kyr BP younger than the 2007 core. The age model of the 2009 core indicates that the core top age would lie somewhere between 0.5 kyr BP and 1 kyr BP based on the accumulation rate and ^{14}C date at 5 cm, while a ^{137}Cs date in the 2007 core suggests a modern, or near modern core top age (Fig S2 and S3). Using this information, the final sequence was constrained to start and end with the 2007 core. A spike in LOI is present in both cores at 110 cm in the 2007 core and 60 cm in the 2009 core and was used as a tie point between the cores, yielding a sequence with three constraints (Fig S3). This configuration resulted in a sequence with a delta value of 0.591 and combined path length of 1038.17 (Fig S3). A delta value of 0.591 is a good fit, with an approximate R value of 0.90 (Thompson and Clark 1990; Gordon et al. 1988).

Table 1

Soil geochemical data from collected from Blue Lake in 2007. Notes of flora at sample site included.

Sample name	**$\delta^{13}C$ (‰)**	**TOC (%)**	**TN (%)**	**C/N**	**Notes**
BL1	-28	4.2	0.3	15.8	Recently burned open woodland, with *Xanthorrea*, very sparse organic matter.
BL2	-27.9	5.2	0.1	55.1	Open woodland, with *Xanthorrea.*
BL3	-29.2	15	0.3	56.9	Eucalypt woodland with *Pteridium* understorey.
BL4	-28.9	11.8	0.2	48.9	Open woodland, with *Xanthorrea.*
BL5	-28.4	7.2	0.1	87	Open woodland, with *Xanthorrea.*
BL6	-27.1	16.2	0.1	169.2	Recently burned open woodland, with *Xanthorrea.*
BL7	-28.4	22.8	0.2	109.2	*Eucalyptus* woodland with *Xanthorrea* understorey, lots of leaf litter.
BL8	-29	17.4	0.3	62.7	Open woodland, scrubbier, more understorey, *Acacia* dominated (understorey).
BL9	-29.7	11	0.2	46.5	*Eucalyptus* woodland moderate leaf litter.
BL10	-28.9	2.7	0.1	22.3	

Table 2

Modern plant and algal data from Blue Lake

Plant and algal samples							
Location	$\delta^{13}C$ (‰)	TOC (%)	TN (%)	C/N	Species (%)	Collection Date	Sample type
Blue Lake	-36.2	20	2.6	9.0	*Hapalosiphon pumilus (97)*	Aug-18	Algae
Blue Lake	-36.1	30.0	2.2	15.7	*Hapalosiphon pumilus/Scytonema mirabile (75/25)*	Aug-18	Algae
Blue Lake	-35.2	38.2	3.4	13.1	*Scytonema mirabile (>95)*	Aug-18	Algae
Blue Lake	-32.3	36.1	2.3	18.6	*Hapalosiphon pumilus (>90)*	Aug-18	Algae
Blue Lake	-25.7	38.6	1.9	23.2	*Symphyonema karboorum*	Aug-18	Algae
Blue Lake	-30.1	41.2	1.2	41.1	*Symphyonema karboorum (95)*	Aug-18	Algae
Blue Lake	-25.5	42.3	1.8	27.9	*Symphyonema karboorum (>90)*	Aug-18	Algae
Blue Lake	-32.1	40.8	2.6	18.1	Unidentified cyanobacteria	Aug-18	Algae
Blue Lake Phytoplankton tow	-37.8	45.9	3.4	13.5	Unidentified	Mar-18	Algae

Blue Lake					*Symphyonema karboorum/Scytonema spp. (90/10)*	Aug-18	Algae
Blue Lake	-30.9	38.6	2.5	15.5	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-31.0	38.8	2.5	15.6	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-32.6	40.4	2.4	17.2	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-31.1	38.3	2.0	19.0	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-29.1	34.5	1.8	18.9	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-27.2	44.6	2.4	18.6	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-25.7	41.9	1.2	36.1	Unidentified cyanobacteria	Jan-18	Algae
Blue Lake	-29.8	36.7	1.0	19.1	Unidentified cyanobacteria	see Cadd et al. (2018)	Algae
Blue Lake	-31.7	38.3	1.6	18.1	*Hapalosiphon* sp.	see Cadd et al. (2018)	Algae
Swallow Lagoon	-27.4	51.1	0.7	72.8	*Leperonia articulata*	see Cadd et al. (2018)	Emergent macrophyte
Welsby Lagoon	-26.7	68.0	0.6	116.5	Baumea sp.	see Cadd et al. (2018)	Emergent macrophyte
Swallow Lagoon	-28.0	66.2	0.5	146.2	Baumea sp.	see Cadd et al. (2018)	Emergent macrophyte
Welsby Lagoon	-24.6	42.8	2.2	19.4	*Cycnogeton procerus*	see Cadd et al. (2018)	Emergent macrophyte
Welsby Lagoon	-26.2	48.4	0.6	81.7	*Leperonia articulata*	see Cadd et al. (2018)	Emergent macrophyte

Blue Lake	-26.8	42.5	0.7	62.8	*Lepironia articulata*	Aug-18	Emergent macrophyte
Blue Lake	-28.4	44.3	0.8	52.1	*Gahnia* sp.	Aug-18	Emergent macrophyte
Blue Lake	-23.1	37.8	2.1	18.0	*Triglochin* sp.	Aug-18	Emergent macrophyte
Blue Lake	-29.4	40.2	0.9	44.2	*Eleocharis difformis*	Aug-18	Submerged macrophyte
Blue Lake	-29.1	40.4	1.0	40.3	*Eleocharis difformis*	Aug-18	Submerged macrophyte
Blue Lake	-29.6	37.0	1.6	23.7	*Myriophyllum* sp.	Aug-18	Submerged macrophyte
Blue Lake	-28.0	42.4	2.4	17.6	*Unknown fungus*	Jan-18	Fungus
Blue Lake	-30.4	48.3	1.1	44.2	*Casuarina* sp.	see Cadd et al. (2018)	Terrestrial
Blue Lake	-31.0	20.4	0.7	29.4	*Eucalyptus* sp.	see Cadd et al. (2018)	Terrestrial
Blue Lake	-31.6	49.0	0.8	58.1	*Banksia* sp.	see Cadd et al. (2018)	Terrestrial
Blue Lake	-29.7	45.2	1.0	47.3	*Eucalyptus* sp. leaves	Aug-18	Terrestrial
Blue Lake	-33.1	49.9	0.5	110.7	*Banksia* sp. leaves	Aug-18	Terrestrial
Blue Lake	-31.4	47.9	1.1	42.5	*Casuarina* sp. leaves	Aug-18	Terrestrial
Blue Lake	-29.0	46.3	0.1	315.0	*Eucalyptus* sp. twigs	Aug-18	Terrestrial

Blue Lake	-29.7	51.4	1.1	45.9	*Casuarina* sp. leaves	Aug-18	Terrestrial
Blue Lake	-29.7	46.6	0.2	192.4	*Casuarina* sp. twigs	Aug-18	Terrestrial
Blue Lake	-30.6	49.5	0.3	194.8	*Banksia* sp. leaves	Aug-18	Terrestrial
Blue Lake	-29.5	48.7	0.1	396.2	*Banksia* sp. twigs	Aug-18	Terrestrial
Blue Lake	-29.4	52.0	0.4	118.6	*Eucalyptus* sp. leaves	Aug-18	Terrestrial

Table 3

Group averages of modern plant types from Blue Lake.

Group averages					
Group	δ^{13}C (‰)	TOC (%)	TN (%)	C/N	n
Terrestrial Plants	-30.3	46.3	0.6	126.7	13
Aquatic Macrophytes	-27.7	47.2	1.1	62.5	10
Algae	-31.0	38.1	2.2	21.6	18
Soil	-28.4	11.4	0.2	67.4	9
Terrestrial Burned	-29.8	51.3	0.6	247.3	42
Fungus	-28.0	42.4	2.4	17.6	1

Table 4

Burned terrestrial samples. *Eucalyptus* (E), *Banksia* (B), and Casuarinacae (C) leaves (L) alive (A) and dead (D) and sticks (ST) burned at different temperatures.

Samples	**$\delta^{13}C$**	**TOC (%)**	**TN (%)**	**C/N**
ELA Dried	-29.7	45.2	1.0	47.3
ELA 250°C	-29.6	51.9	1.1	48.4
ELA 500°C	-29.7	70.3	1.6	43.5
ELA 750°C	-29.6	77.7	1.7	44.8
ELA 750°C - NL	-27.1	4.7	0.0	424.9
BLA Dried	-33.1	49.9	0.5	110.7
BLA 250°C	-33.0	56.3	0.5	109.3
BLA 500°C	-33.2	73.4	0.7	110.0
BLA 750°C	-33.4	78.6	0.7	119.7
BLA 750°C - NL		1.4		
CLA Dried	-31.4	47.9	1.1	42.5
CLA 250°C	-29.6	57.9	0.6	94.7
CLA 500°C	-31.4	72.2	1.8	40.7
CLA 750°C	-31.4	75.3	1.5	51.1
CLA 750°C - NL	-28.9	4.3	0.0	328.5
EST Dried	-29.0	46.3	0.1	315.0
EST 250°C	-28.8	51.7	0.2	295.3
EST 500°C	-29.5	73.3	0.3	229.6
EST 750°C	-29.4	79.8	0.3	287.9
EST 750°C - NL	-28.3	7.6	0.0	1084.6
CLD Dried	-29.7	51.4	1.1	45.9
CLD 250°C	-29.6	52.8	1.2	44.9
CLD 500°C	-29.8	69.1	2.2	32.0
CLD 750°C	-30.4	82.9	1.5	55.3
CLD 750°C - NL	-28.9	11.4	0.3	43.4
CST Dried	-29.7	46.6	0.2	192.4
CST 250°C	-29.6	47.9	0.3	164.6
CST 500°C	-30.5	77.9	0.6	130.3
CST 750°C	-30.9	82.1	0.5	160.0
CST 750°C - NL	-30.2	9.3	0.0	2336.5
BLD Dried	-30.6	49.5	0.3	194.8
BLD 250°C	-30.4	52.6	0.3	182.1
BLD 500°C	-30.7	67.5	0.5	140.4
BLD 750°C	-31.0	75.5	0.3	237.5
BLD 750°C - NL		4.6	0.0	763.2
BST Dried	-29.5	48.7	0.1	396.2
BST 250°C	-29.4	54.8	0.2	356.0

BST 500^{o}C	-30.5	72.1	0.4	167.7
BST 750^{o}C	-30.9	86.4	0.2	359.8
BST 750^{o}C - NL	-30.8	6.5		
ELD Dried	-29.4	52.0	0.4	118.6
ELD 250^{o}C	-31.2	51.1	1.0	51.6
ELD 500^{o}C	-29.4	67.2	1.2	58.2
ELD 750^{o}C	-29.3	52.9	0.8	67.1
ELD 750^{o}C - NL	-28.3	8.0	0.0	802.8

Table 5

Surface soil LOI estimated organic matter data.

Soil surface organic matter samples	
Sample	LOI (%)
1.1	95.1
1.2	95.4
1.3	98.2
3.1	94.3
3.2	97.6
3.3	95.4
4.1	96.2
4.2 leaf	71.9
4.2	90.3
4.3	89.5

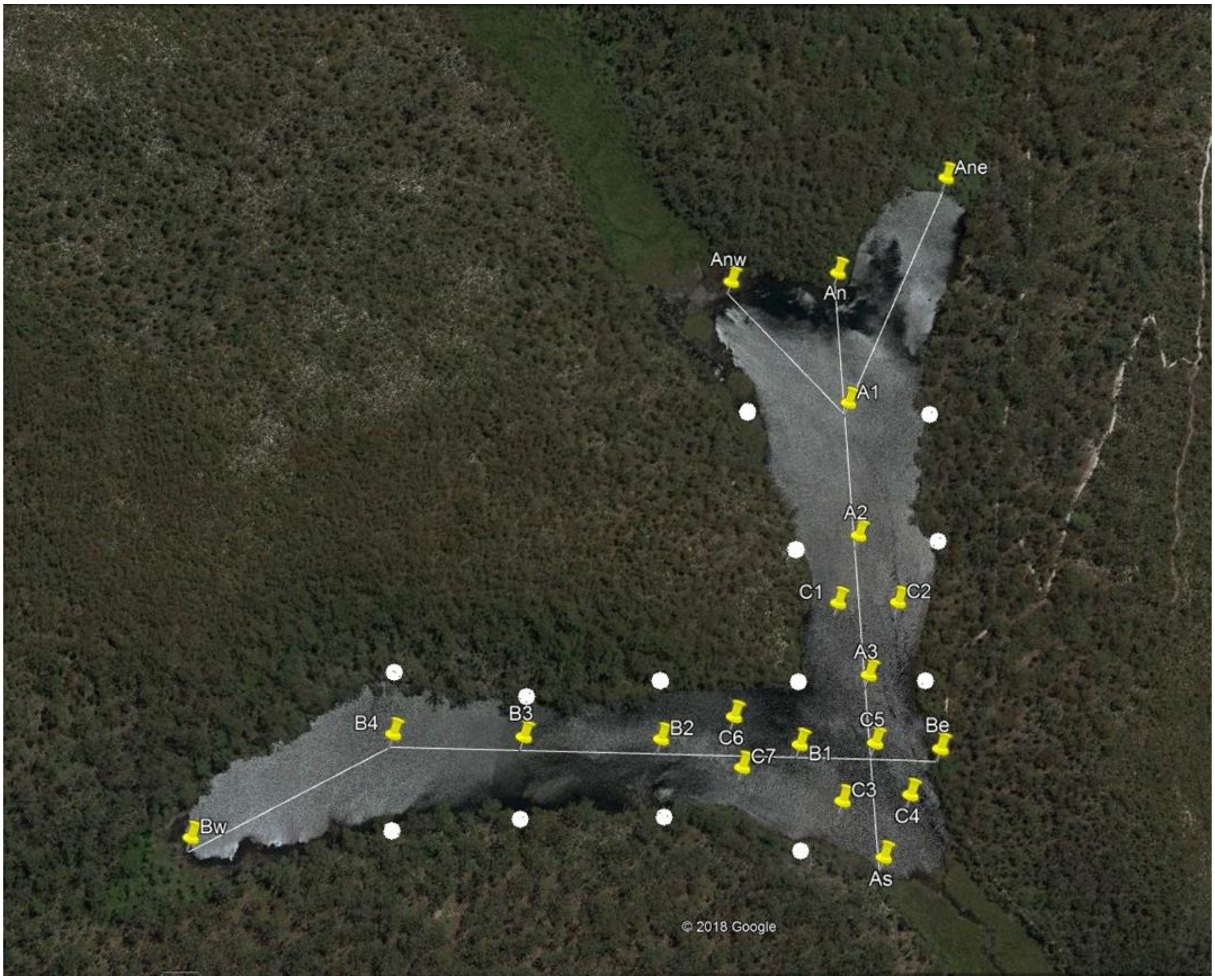


Figure 1: Sampling of Blue Lake. White dots represent sites for sampling and habitat survey. White lines represent the two transects in the lake. Pins labelled A# or B# represent latitude (N-S arm) and longitude (E-W arm) of sampling points. Pins labelled C# represent deep survey sites for ROV.

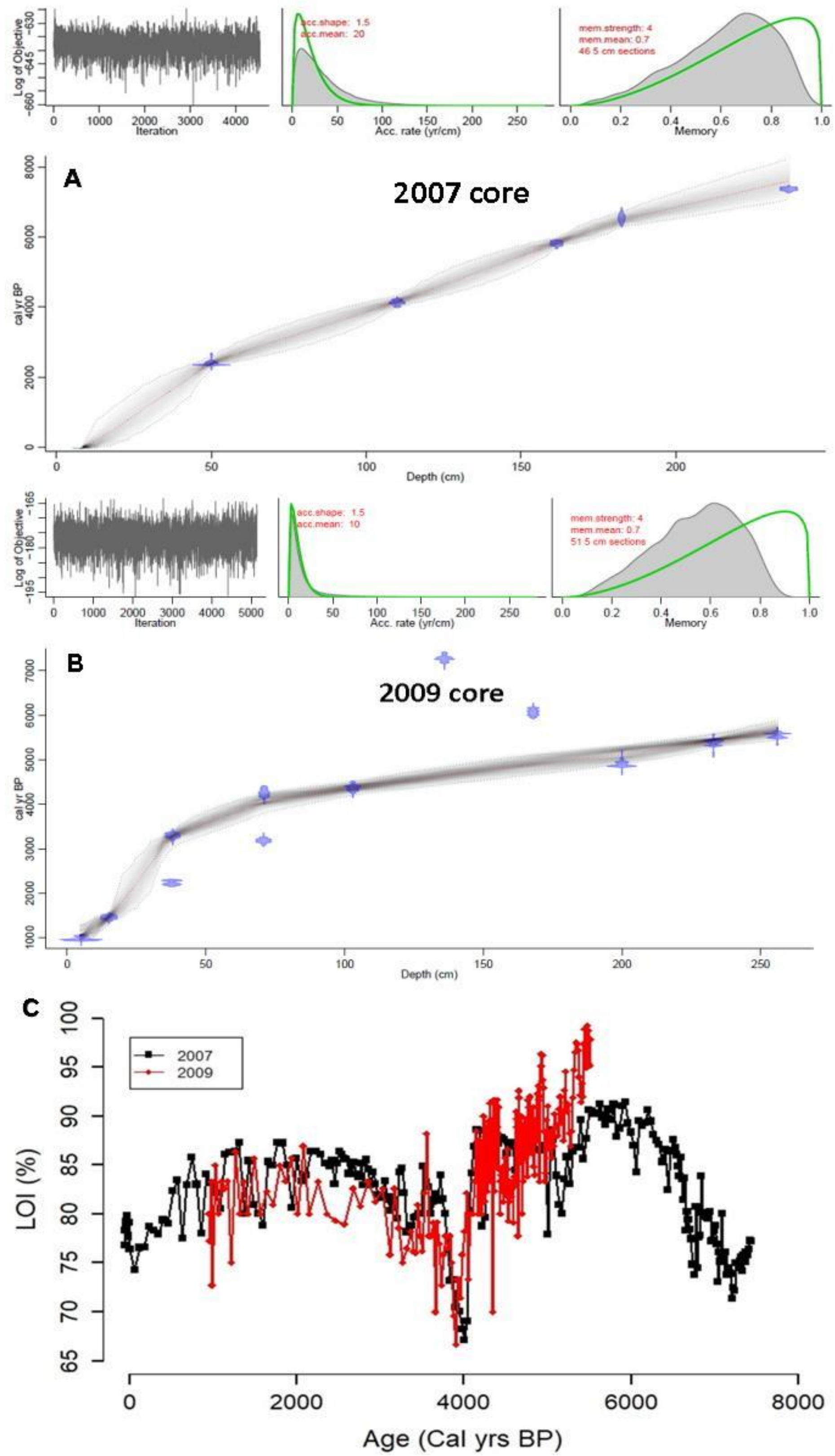


Figure 2: Individual age models for the (A) 2007 and (B) 2009 cores. (C) LOI vs. age for each core showing their shared pattern.

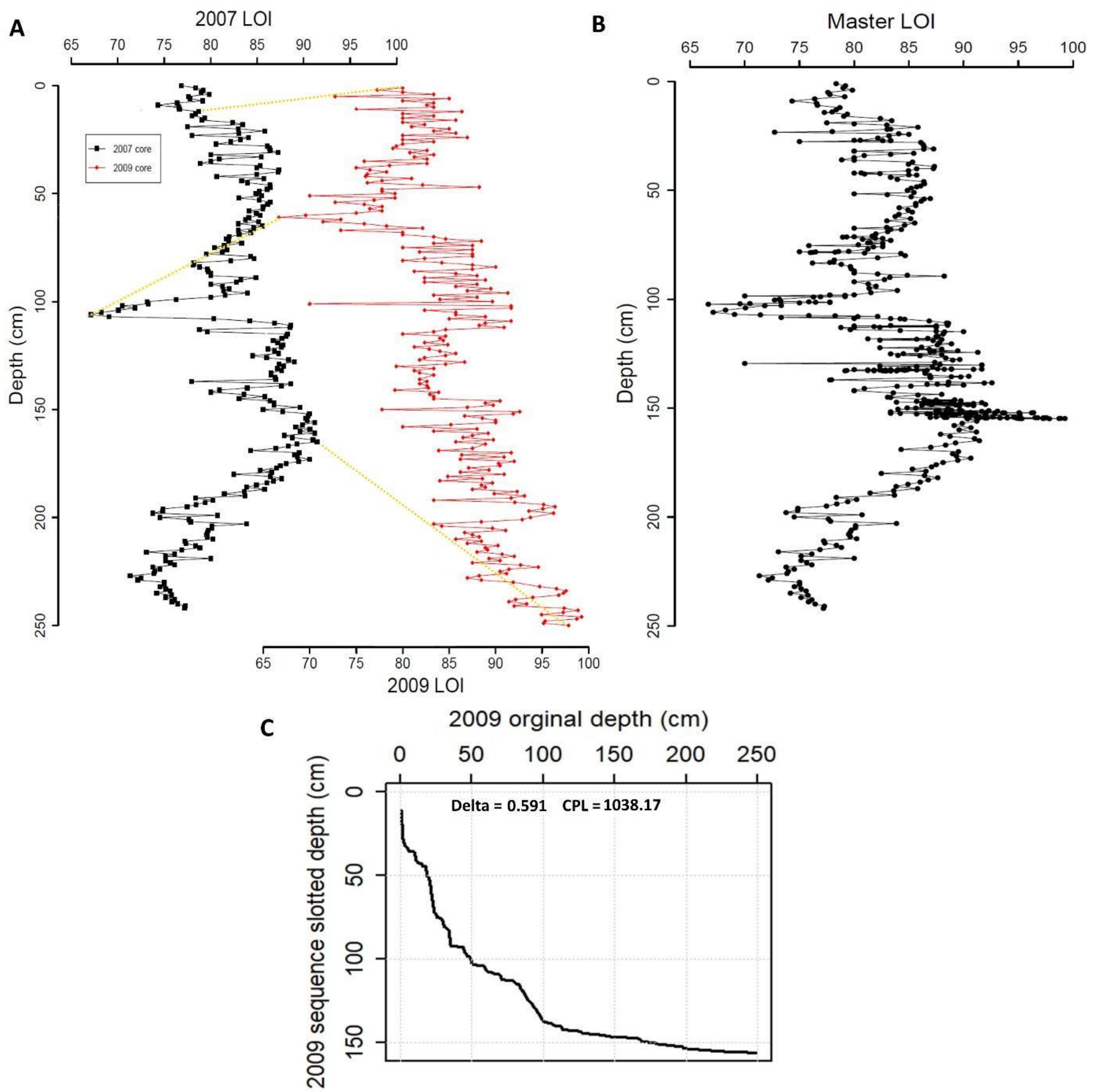


Figure 3: Sequence slotting of the 2007 and 2009 cores. A) shows 2007 (black) and 2009 (red) LOI against depth with the tie points used in the slotting procedure (gold). B) is the result of the slotting procedure and C) shows the wellness of fit of the 2009 core into the master sequence.

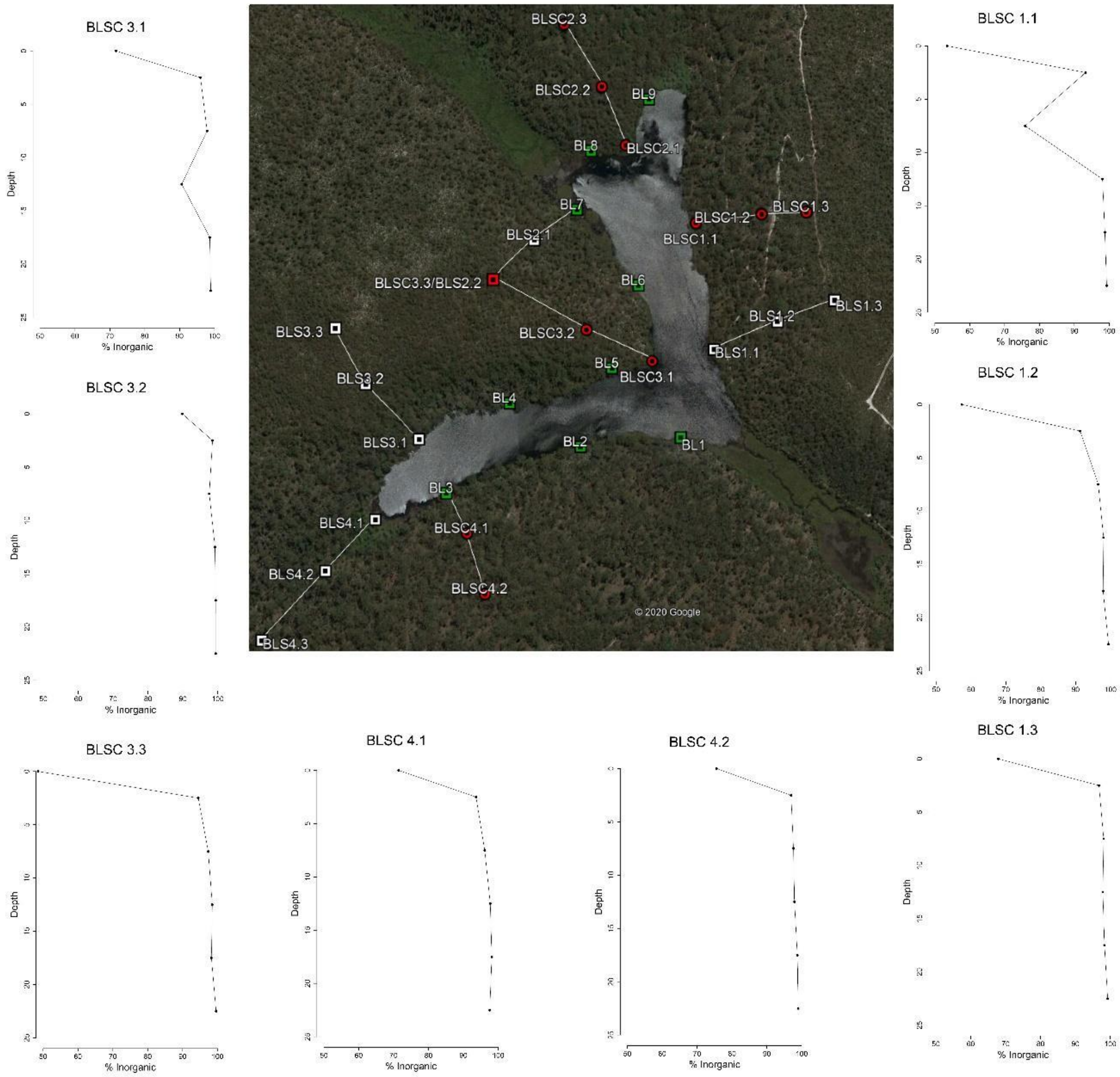


Figure 4: Soil sampling map of surface samples (white squares; Table S5), 25 cm cores (red squares), and soil geochemical samples (green squares). Profiles show each 25 cm core with depth plotted against inorganic matter.

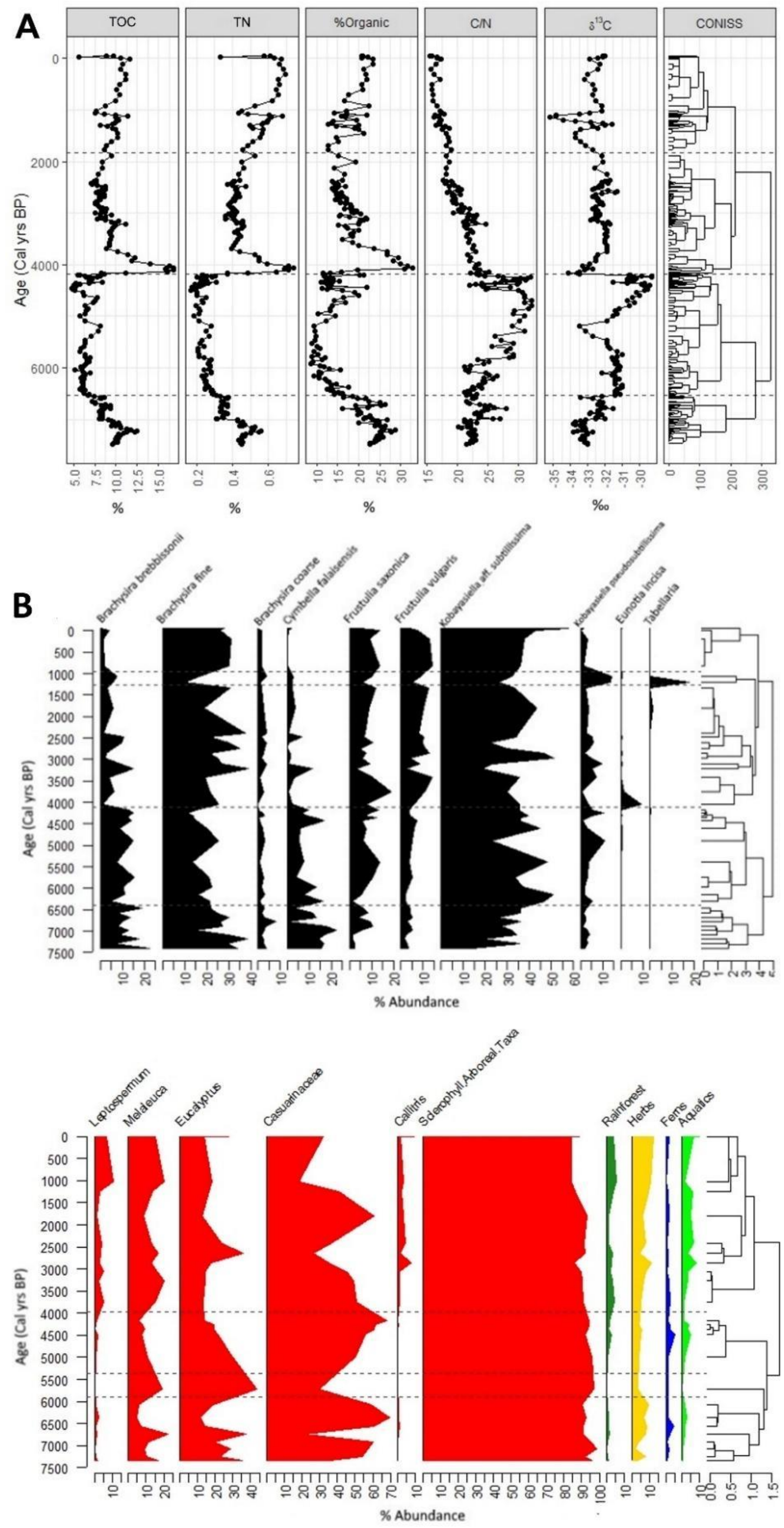


Figure 5: CONISS analysis of geochemistry (A), diatom (B), and pollen (C) stratigraphy, indicating coherent timing of the dominant change in all proxies.

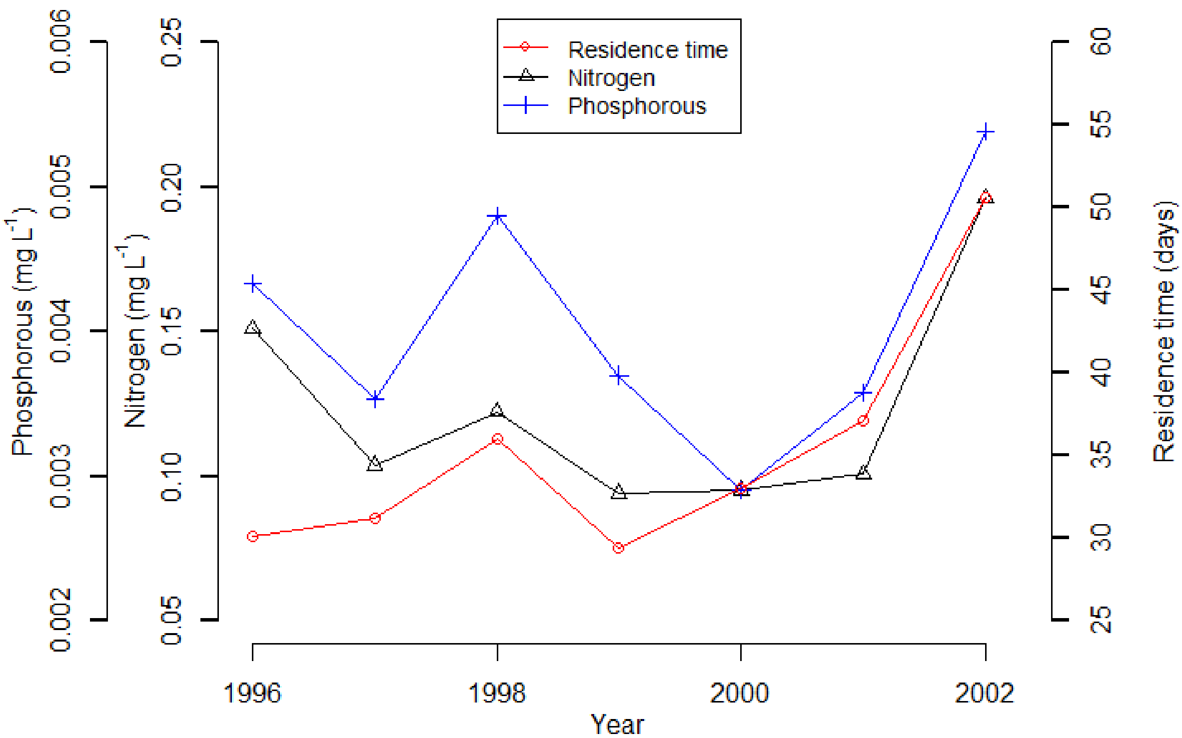


Figure 6: Residence time of water in Blue Lake and nitrogen and phosphorous concentrations of lake water from Blue Lake between 1996 and 2002. Residence time calculated from lake and outflow stream volume data (Barr et al. 2013).

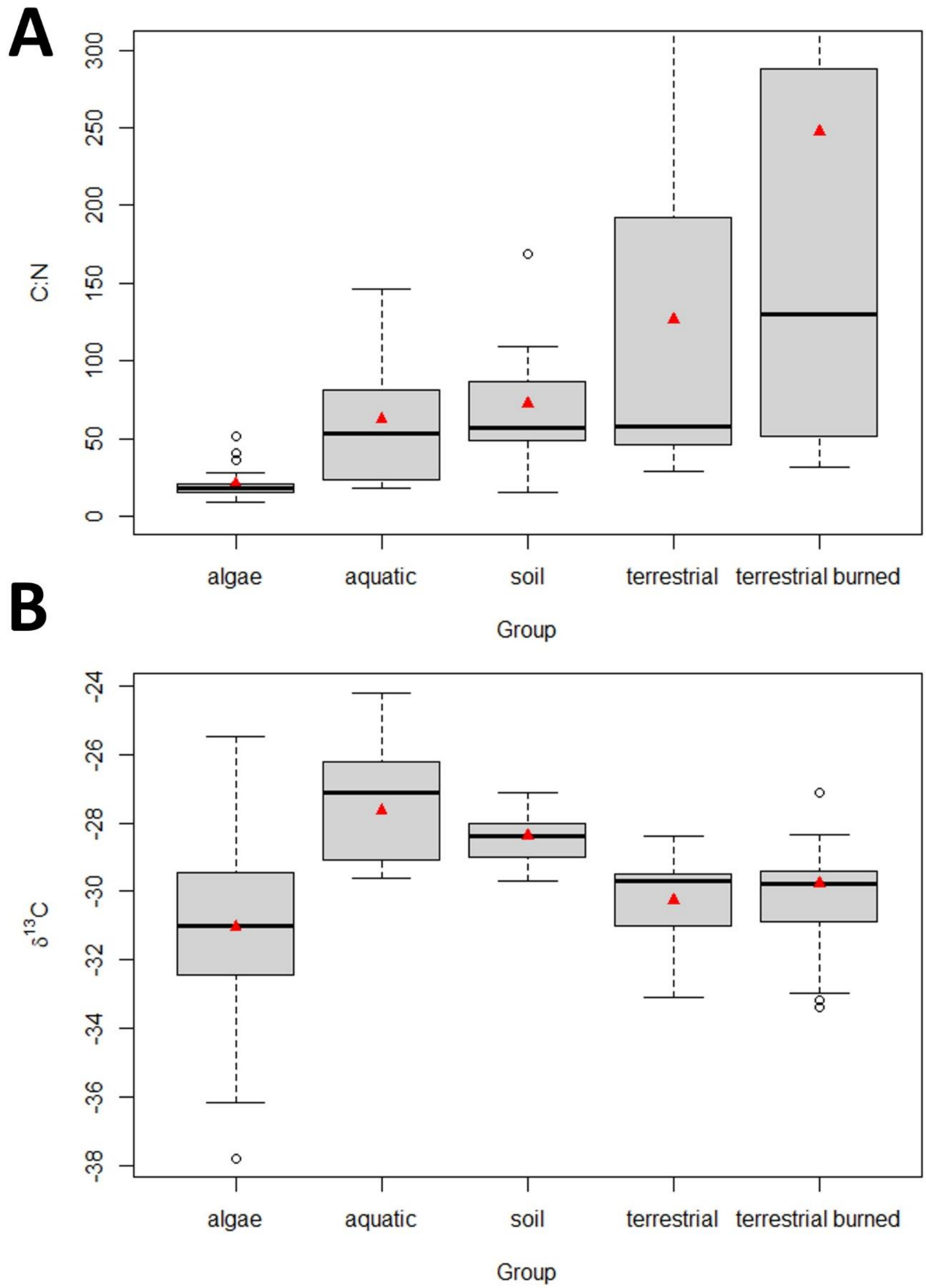


Figure 7: Box and whisker plots of (A) C:N and (B) $\delta^{13}C$ data sorted by group. Median denoted with bold black line, mean by red triangles, interquartile zone by grey box, max and min by lines, and outliers by circles

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