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Vegetation and water quality responses to Holocene climate variability in Lake Purrumbete, western Victoria

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Introduction

Palaeoenvironmental research can provide useful perspectives about the vulnerability and resilience of ecosystems to future climate change by documenting ecosystem response to past natural and human-induced environmental change (e.g. Dearing 2008, 2011). Such information is important since instrumental records for all but a few localities are non-existent, or are temporally short relative to ecological timescales (Smol 2008) and because ecosystem changes are, or will soon be, beyond the magnitude of anything witnessed in the historical period (Hansen 2005).

Between 1997 and 2010, lakes in western Victoria responded to prolonged hydrological deficit in a range of ways. Many dried out, while the vast majority underwent substantial changes in water quality and ecology (Leahy et al. 2010). Recent research has shown that a number of lakes once thought to be permanent landscape features are now subject to drying, while many

other lakes are projected to be seasonally dry by the end of the 21st century (Leahy et al. 2010). The present water quality and ecology of Western District Ramsar-listed lakes (lakes Beeac, Bookar, Colongulac, Corangamite, Cundare, Gnarput, Milangil, Murdeduke and Terangpom) bears little resemblance to their conditions when listed under the Ramsar agreement in 1982, and most have been at least seasonally dry over the past decade. Given that there has been a very substantial reduction in the number of western Victorian lakes, including those recognised as nationally and internationally significant, ecosystem preservation in the remaining lakes is paramount. Of the numerous lakes in western Victoria, a small number of deeper sites (>5 m deep) will persist throughout the 21st century, even with marked hydrological deficit (Kirono et al. 2009). Given that deep lakes will be important landscape refugia over this century, prudent management is important. Although the limnology of western Victorian lakes is relatively well studied (e.g. Timms 1976; De Deckker 1983; De Deckker and Williams 1988; Tibby and Tiller 2007), there is still considerable uncertainty about their likely future behaviour. With the aim of enhancing understanding of its possible future behaviour, this study focuses on the environmental history of one such lake: Lake Purrumbete, the deepest natural freshwater lake in Victoria.

Previous palaeoenvironmental studies at Lake Purrumbete have been undertaken by De Deckker (1982) and Yezdani (1970). However, these studies were based on records that were undated and also, in the case of Yezdani (1970), short. Yezdani (1970) briefly described the pollen and algae (including diatoms) at a coarse resolution from a core collected near the edge of the lake. All the samples were post-European, as indicated by the presence of *Pinus* pollen throughout the record. De Deckker's (1982) macrofossil record for Purrumbete was not radiocarbon dated, however the 580 cm record was suggested to cover about 6000-7000 years, an inference largely consistent with the results herein. De Deckker (1982) inferred a constantly fresh lake with water depth >35 m throughout the record. However, the proxies used by De Deckker did not allow fine-scale estimation of palaeoclimatic changes.

Lake Purrumbete has one of the longest records of continuous water-quality monitoring in Victoria (Mitchell and Collins 1987; Tibby and Tiller 2007). These data are important to the management of this and other lake systems. In particular, such data can be used to predict future responses to climate change through coupling with dynamic climate modelling such as the Kirono et al.'s (In press) modelling of salinity response to predicted climate in the western Victorian lakes Bullenmerri, Gnotuk and Keilambete. Although valuable, such exercises are limited because modelling of climate-driven biological responses is considerably more difficult than predicting physical responses (such as changes in lake depth, salinity or stratification). Climate projections for southwestern Victoria consistently predict increased temperature, while rainfall estimates are somewhat more variable (i.e. while most model predictions infer future declines in rainfall, some suggest there may be rainfall increases, CSIRO and BOM 2007). However, the combined effect of temperature increases and changes in rainfall is likely to result in reductions in effective precipitation (Kirono et al. In press). Combining future climate scenarios with the observed behaviour of lakes makes it possible to hypothesise about the response of lakes to future warming, although it is axiomatic that such models are calibrated over short time periods relative to often lengthy ecosystem responses to climate change.

Building on the earlier research of Mitchell and Collins (1987), Tibby and Tiller (2007) analysed the relationship between Lake Purrumbete water quality and climate for the period 1984-2000. In line with expectations, they demonstrated that lake salinity (measured as electrical conductivity) increased in response to reduced effective moisture and that water temperature was strongly correlated with air temperature. In addition, they also showed that there was a strong negative relationship between air temperature and nutrient concentrations (specifically total phosphorus) in the water column ($r^2 = 0.61$, $p < 0.005$, $n = 165$). Tibby and Tiller (2007)

suggest that periods of increased temperature lead to lengthened periods of water column stratification. This, in turn, results in nutrients being depleted from the epiliminion through the uptake of phosphorus by algae, which eventually sink, sequestering nutrients to the sediments.

Based on a combination of these observations about future warming and Lake Purrumbete's relationship to measured climate, it appears that future change may be expected to increase water temperature and salinity, while decreasing average water-column nutrient concentrations. In order to assess this scenario, therefore, we utilised a long-term record of environmental change preserved in Lake Purrumbete sediments to examine the nature of the Lake's response to (past) climate change, with a view to more fully understanding the possible nature of future change. This approach arose from observations that the diatom records from this and other western Victorian lakes including Lake Surprise (Tibby et al. 2006) and Tower Hill Lake (D'Costa et al. 1989) exhibit very marked shifts during the Holocene, suggesting lacustrine conditions that are very different to those recorded in even relatively long monitoring time series.

Our analysis focuses predominantly on the pollen and diatom record derived from a 6 m Mackereth core extracted from Lake Purrumbete in the late 1990s. In addition, pollen data are derived from an associated frozen spade core, representing an undisturbed record of the most recently deposited sediments. We utilise the record of precipitation-evaporation ratio (P:E) derived from nearby Lakes Keilambete, Gnotuk and Bullenmerri (Jones et al. 1998, see Figure 1 for site locations) as a means of interpreting the response of the aquatic and terrestrial ecosystems in Lake Purrumbete and its surrounds to climate variability. Although there are differing interpretations of the precise timing of changes in these records (particularly from the most intensively studied Lake Keilambete), there is a coherent record of effective precipitation inferred by a number of authors using a variety of proxies including sediment grain size and composition, ostracod composition and shell chemistry, and pollen (Dodson 1974; Bowler 1981; De Deckker 1982; Chivas et al. 1985; Jones et al. 1998), which, importantly, have been observed in other lakes in the region (Gell 1998; Tibby et al. 2006). While it is not possible to de-couple the separate effects of precipitation and evaporation in Jones et al.'s (1998) record, it nevertheless provides a quantitative estimate of effective moisture through the Holocene. Hence, we use the P:E record as a reference point to examine how water quality and vegetation in and around Lake Purrumbete responded to arid and humid phases during the Holocene. Importantly, the inferred effective moisture history from western Victoria can be compared with the inferred effective moisture history predicted for the region (Kirono et al. 2009), allowing future likely changes to be placed in context.

Study site

Lake Purrumbete is a large, fresh, clear-water, alkaline, eutrophic maar crater (see Table 1 for summary water-quality information). It has a maximum breadth of more than 2.8 km, a maximum depth of 45 m, a surface area of more than 5.5 km² and a volume of 157 x 106 m³ (Timms 1976). Vegetation surrounding the lake, as for the region in general, is heavily modified by recent land use. Remnant native vegetation can be broadly classified as grasslands or open grassy woodlands (Kershaw et al. 2004), with strong edaphic controls on vegetation apparent, particularly with respect to the distribution of soils weathered from basalt (D'Costa et al. 1989).

Ecological studies of Lake Purrumbete began in the late 1960s (Hussainy 1969; Yezdani 1970; Timms 1976). Both Hussainy (1969) and Yezdani (1970) noted the presence of spring blooms of *Melosira granulata* (=*Aulacoseira granulata*) over a period of three years. Gasse et al. (1997) showed that the dominant planktonic diatoms in the centre of Lake Purrumbete sampled in sediment traps, and to a lesser extent phytoplankton sweeps, were *Cyclotella meneghiniana*
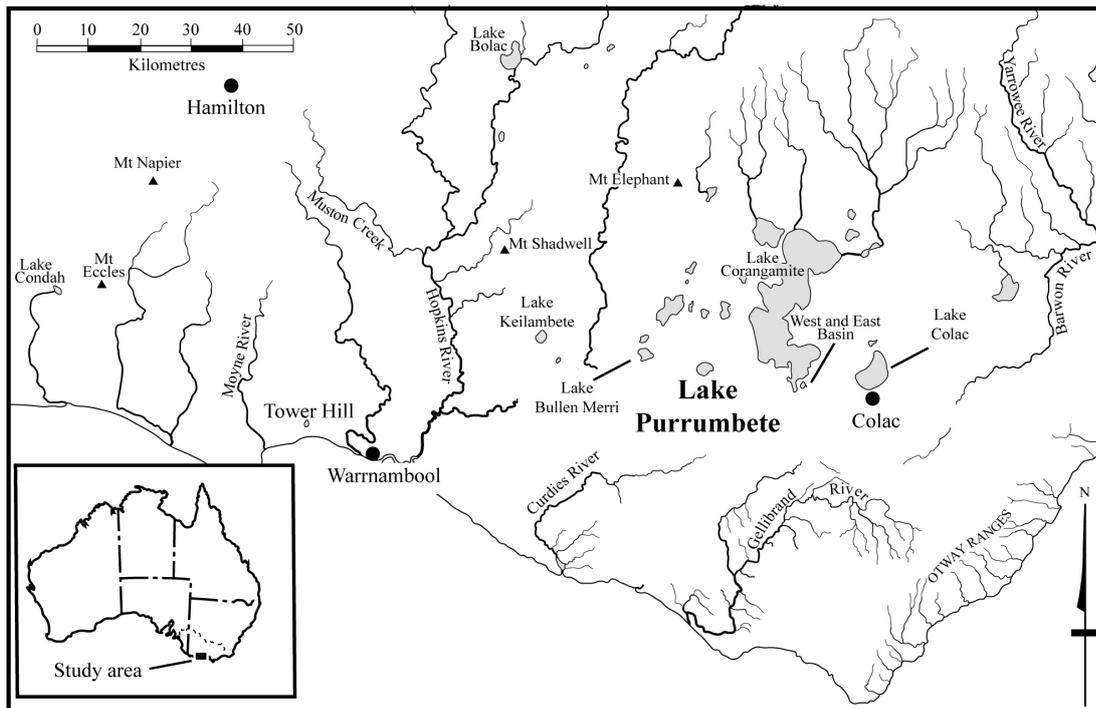
Figure 1. Location of Lake Purrumbete and other sites referred to in the text.

Table 1. Summary of water quality data from Lake Purrumbete 1984-2000. See Tibby and Tiller (2007) for details of methods.

Variable	Unit	Average	*n* determinations
Water temperature	°C	15.2	179
Electrical conductivity	µS cm^{-1}	739	180
pH	pH Units	8.6	175
Total nitrogen	mg l^{-1}	0.792	178
Total phosphorus	mg l^{-1}	0.102	178
Orthophosphate (PO$_4$)	mg l^{-1}	0.083	176
Dissolved oxygen	mg l^{-1}	9.749	180
Turbidity	NTU	1.155	148
Secchi depth	metres	4.6	81

and *Aulacoseira granulata*. Interestingly, they also noted that, in summer phytoplankton sweeps, the epiphytic diatom *Cocconeis placentula* is the most abundant diatom, despite the substantial distance of their study site from the shoreline.

Despite the relative longevity of ecological study at Lake Purrumbete, palaeoecology can provide additional information to facilitate better lake management. For example, aquatic macrophyte surveys in the late 1960s (Yezdani 1970) did not detect the current dominant macrophyte in the lake *Vallisneria americana* var. *americana* (EPA Victoria, unpub. data). In the late 1960s, *Myriophyllum* spp. were dominant (Yezdani 1970). Mitchell and Collins (1987) detected *Vallisneria gigantea* (= *Vallisneria americana* var. *americana*) in Lake Purrumbete by 1984. From the perspective of lake managers, it is not clear whether the current dominance by *Vallisneria* is related to recent shifts in climate, the lake nutrient status, or part of natural variability.

Methods

Sediment coring was undertaken from an anchored floating platform close the centre of the lake. A near 6 m long core, 5 cm in diameter, was collected with a Mackereth sampler

(Mackereth 1958). As the corer tends to disturb or fail to collect very unconsolidated surface sediments, material from the topmost 1 m was retrieved intact on a frozen spade (Neale and Walker 1996).

Samples of 1 cm^3 were taken at 10 cm intervals (n=59) from the Mackereth core and prepared for diatom analysis using a modification of Battarbee (1986), where three-hour treatments in 10% HCl and 10% H_2O_2 were used to remove carbonate and organic matter, respectively. Following these treatments, samples were rinsed repeatedly in distilled water, and they were then mounted using Naphrax mounting medium. Diatoms were identified using 1000x magnification with a Zeiss Axioskop fitted with differential interference contrast, with Krammer and Lange-Bertalot (1986, 1988, 1991a, b) the main source of taxonomic information. A minimum of 300 valves were counted per sample, with diatom abundances calculated using the microspheres method described in Battarbee (1986).

Separation cells of *Aulacoseira granulata* were identified, as Gomez et al. (1995) have shown that *A. granulata* forms a larger number of separation cells during periods of stratification, so that its filament (or "chain") is shorter, rendering it easier for such chains to remain suspended in poorly mixed water columns.

Samples of 2 cm^3 of wet sediment were extracted from the core and the frozen spade for pollen analysis, with sampling resolution increasing from a maximum of 0.4 m below 3.0 m depth to a minimum of 0.04 m in the frozen-spade sample, which represents the upper 0.6 m of the pollen record (n=37). The Mackereth core and the frozen-spade sample were correlated using the first appearance of introduced *Pinus* pollen in both records as a biostratigraphic marker. The samples were prepared following the method of van der Kaars et al. (2000) and pollen grains counted at 400x magnification with an Olympus CH-2 microscope. Pollen counts ranged between 133 and 406, with an average of 259 palynomorphs per sample. Taxonomy was based primarily on an extensive modern reference set in the School of Geography and Environmental Science, Monash University. Pollen and spore counts are expressed as abundance relative to a standardised dryland pollen sum for southeastern Australia (D'Costa and Kershaw 1997). *Banksia* was excluded from the standard pollen sum in order to avoid distortion in the data set due to extreme over-representation of this taxon at 0.4 m depth in the core. Pollen and diatom relative abundance data (excluding *Banksia* and taxa <1% respectively) were classified into zones using a stratigraphically constrained cluster analysis with Euclidean distance as the similarity metric (Grimm 1987). Pollen and diatom zone boundaries were established at arbitrary thresholds of 0.6 and 3.0 respectively.

Four pollen concentrates (prepared following Regnell 1992) were submitted for accelerator mass spectrometry radiocarbon dating (Fink et al. 2004). Radiocarbon ages (BP) were calibrated (cal BP) using the INTCAL09 dataset (Reimer et al. 2009) in the programme CALIB 6.0 (Stuiver and Reimer 1986). The resulting calibrated ages (Table 2) have a near-linear relationship with depth (r^2=0.992), and a simple linear regression was used as a basis for the chronological model used in Figures 2 and 3.

Results

Diatom and pollen results are presented in Figures 2 and 3, respectively. Diatom zone 4 is characterised by the highest relative abundances of non-planktonic taxa in the record, although the planktonic *Aulacoseira granulata* is the species with the highest individual relative abundance. Of the non-planktonic diatoms, the major taxa are *Fragilaria* aff. *zeilleri*, *Pseudostaurosira brevistriata*, *Staurosirella pinnata* and *Staurosira elliptica*. The relative abundance of non-planktonic diatoms, both in total and individually, is lower in Zone 3. Zone 2 is dominated by *Aulacoseira granulata* and the concentration of diatoms is lowest in this zone. In Zone 1,

Table 2. Results of AMS radiocarbon analysis on pollen concentrates. [14]C ages are calibrated using the program CALIB 6.0 (Stuiver and Reimer 1986) with the INTCAL 09 dataset (Reimer et al. 2009). Ages are reported at 1σ (68.3%) and 2σ (95.4%) confidence, and the relative area of the probability distribution for each intercept of the calibration curve is given in square brackets.

Depth (cm)	Lab code	[14]C age BP	% modern C	Cal BP (1σ)	Cal BP (2σ)
64-65	OZG077	450 ± 35	94.55 ± 0.37	494-526 [1]	340-347 [0.013] 459-540 [0.987]
275-278	OZG076	3660 ± 40	63.38 ± 0.31	3903-3991 [0.771] 4041-4072 [0.229]	3865-4088 [1]
405-408	OZG075	4970 ± 40	53.84 ± 0.26	5652-5746 [1]	5606-5758 [0.849] 5822-5885 [0.151]
575-577	OZG074	7160 ± 50	41.03 ± 0.24	7880-7887 [0.061] 7932-8003 [0.939]	7848-8026 [1]

Discostella stelligera is the dominant diatom in every sample, although its abundance is lower in the upper four samples. The concentration of diatoms is highest in Zone 1.

The pollen record has been divided into three zones based on stratigraphically constrained cluster analysis. Zone 3 (580-170 cm depth; ca. 7600-1700 cal BP) is consistently dominated by Poaceae pollen, averaging 40% of the pollen sum. Common sclerophyll woodland taxa (*Eucalyptus*, Casuarinaceae) are strongly represented with some variability but no clear trend. Cyperaceae and *Myriophyllum* are the most commonly recorded aquatic pollen types in this zone, but their abundance is low and highly variable. The common dryland pollen types are stable throughout Zone 2 (160-36 cm; ca. 1500-150 cal BP), with a slight decline in the relative abundance of Causarinaceae pollen as depth decreases. The very high values for *Banskia* recorded at 40 cm depth are likely a result of over-representation, perhaps due to the interment of flower parts in the sediment, and are not taken as indicative of a change in catchment vegetation. Cyperaceae pollen becomes more abundant, with some variability, through Zone 2, reaching a maximum at 44 cm depth (190 cal BP). Zone 1 of the pollen record (32-0 cm depth; 130 cal BP-present) is characterised by a dramatic increase in the relative abundance of Poaceae pollen (to an average of 83% of the pollen sum), and concomitant decreases in all other dryland pollen taxa in the sum. Pollen from exotic plants (*Pinus*, *Plantago lanceolata*, Cupressaceae) appears for the first time in the record at 40 cm depth (ca. 170 cal BP) and increases dramatically to a maximum relative abundance at 16 cm depth (ca. 50 cal BP). *Myriophyllum* pollen increases at the Zone 2/Zone 1 boundary, to reach a maximum value in Zone 1 at 16 cm depth (ca. 50 cal BP), the strongest representation of that taxon for the entire record. This pattern is not apparent in any of the other aquatic plants in the record (*Triglochin*, *Ruppia*, *Potamogeton*). Cyperaceae, most probably occupying a narrow littoral margin of the steep-sided crater, is poorly and irregularly represented in Zone 1.

Discussion

Diatom and inferred water-quality response to Holocene climate variability

There have been substantial and dramatic changes to the Lake Purrumbete diatom community since 8000 cal BP, with some species completely absent from the early or late part of the record and rapid shifts in the abundance of the dominant and sub-dominant taxa. In Zone 4, from approximately 8000 to 5500 cal BP, non-planktonic diatoms, particularly taxa in the Fragiliariaceae, are more numerous in total than planktonic species, although the planktonic diatom *Aulacoseira granulata* is the single most abundant species. *Aulacoseira granulata*, although variable, declines through this period. Of the non-planktonic species, *Fragilaria* aff. *zeilleri* is the most abundant. However, the taxonomic and therefore the ecological affinity of this taxon is uncertain, apart from the likelihood that, similar to other chain-forming Fragiliariaceae

(Bennion et al. 2001; Sayer 2001), it is not planktonic. The second most abundant non-planktonic diatom is *Pseudostaurosira brevistriata,* which peaks in the middle part of this zone. *Pseudostaurosira brevistriata*, *Staurosirella pinnata* and *Staurosira elliptica* are abundant in shallow lakes (<5 m deep) in Australia (e.g. Gell et al. 2002; Tibby et al. 2007) and elsewhere (Bennion et al. 2001; Sayer 2001).

Given that Lake Purrumbete is currently >40 m deep and that De Deckker (1982) suggests that there is little evidence for marked lake level changes in the lake, the high relative abundance of non-planktonic diatoms 8000-5500 cal BP is intriguing, since it would tend to indicate, *a priori*, a lake depth considerably shallower than 40 m. This is particularly the case since other palaeoenvironmental records from the region (e.g. Bowler 1981; D'Costa et al. 1989) and Jones et al.'s (1998) P:E record indicate that this period was one of maximum water availability (with P:E up to 1.1 during this period). The abundance of *Aulacoseira granulata* in combination with the Fragiliariaceae provides a possible insight into this conundrum since *Aulacoseira granulata* is a diatom that requires turbulent mixing to remain suspended in the water column (Bormans and Webster 1999). Hence, it is likely that the high relative abundance of this colonial taxon, as opposed to solitary planktonic species such as *Discostella stelligera* and *Cyclostephanos dubius*, represents times when wind-generated mixing is elevated (see Wang et al. 2008). Thus, it is possible that the relatively high representation of the Fragiliariaceae may result from these taxa being transported to the central lake environment by the same mixing that advantaged *A. granulata*. Notably, Gasse et al. (1997) report that a large proportion of diatoms they inferred to be derived from the littoral zone were found in centre-lake sediment traps from Lake Purrumbete.

From approximately 5500 cal BP to 4000 cal BP (Zone 3), the dominant diatom is the planktonic species *Cyclostephanos dubius*, which generally increases in relative abundance through this zone (Figure 2). This taxon is abundant during a period of decreased effective moisture where the precipitation:evaporation ratio was between 0.89 and 0.94 (Jones et al. 1998) (see Figure 2). Indeed, the dominance of *Cyclostephanos dubius* commences concurrently with an inferred step change in regional moisture at 5500 cal BP (Jones et al. 1998). *Cyclostephanos dubius* is commonly found in lakes with elevated nutrient concentrations (Bradshaw and Anderson 2003). In northwest European lakes, it has a total phosphorus optimum of 176 μg l^{-1} (Bradshaw and Anderson 2003), while Tibby (2004) derived an optimum of 76 μg TP l[-1] for *Cyclostephanos* aff. *dubius* (maximum relative abundance < 9%), which may be closely related to *C. dubius*, in southeast Australian water storages. *C. dubius* has not been recorded in modern Australian lake sediments at abundances as great as in the Lake Purrumbete record, including in western-Victorian diatom calibration data sets (Gell 1997; Barr 2010).

Given Tibby and Tiller's (2007) observation that water-column nutrient concentrations decrease in Lake Purrumbete as a result of persistent stratification during extended warming, it might be expected that the decreased effective moisture experienced from 5500 cal BP to 3500 cal BP would be associated with *decreased*, rather than increased, nutrient concentrations. Despite this, the increasing abundance of *C. dubius* in the mid Holocene mirrors the decreased moisture witnessed in Lakes Keilambete, Bullenmerri and Gnotuk. As a result, while it could be expected that nutrients would be removed from the water column as a result of longer periods of stratification associated with higher temperatures, and/or less nutrients being delivered to the lake via rainfall, epilimentic nutrient concentrations in Lake Purrumbete remained high through this period.

There was a relatively rapid turnover of species between 4000 cal BP and 3500 cal BP, with *Cyclostephanos dubius* giving way to *Discostella stelligera* after a short (approximately 500-year) phase of *Aulacoseira granulata* dominance. The sustained abundance of *Aulacoseira granulata*, with its requirement for water column turbulence, likely indicates a period of greater wind
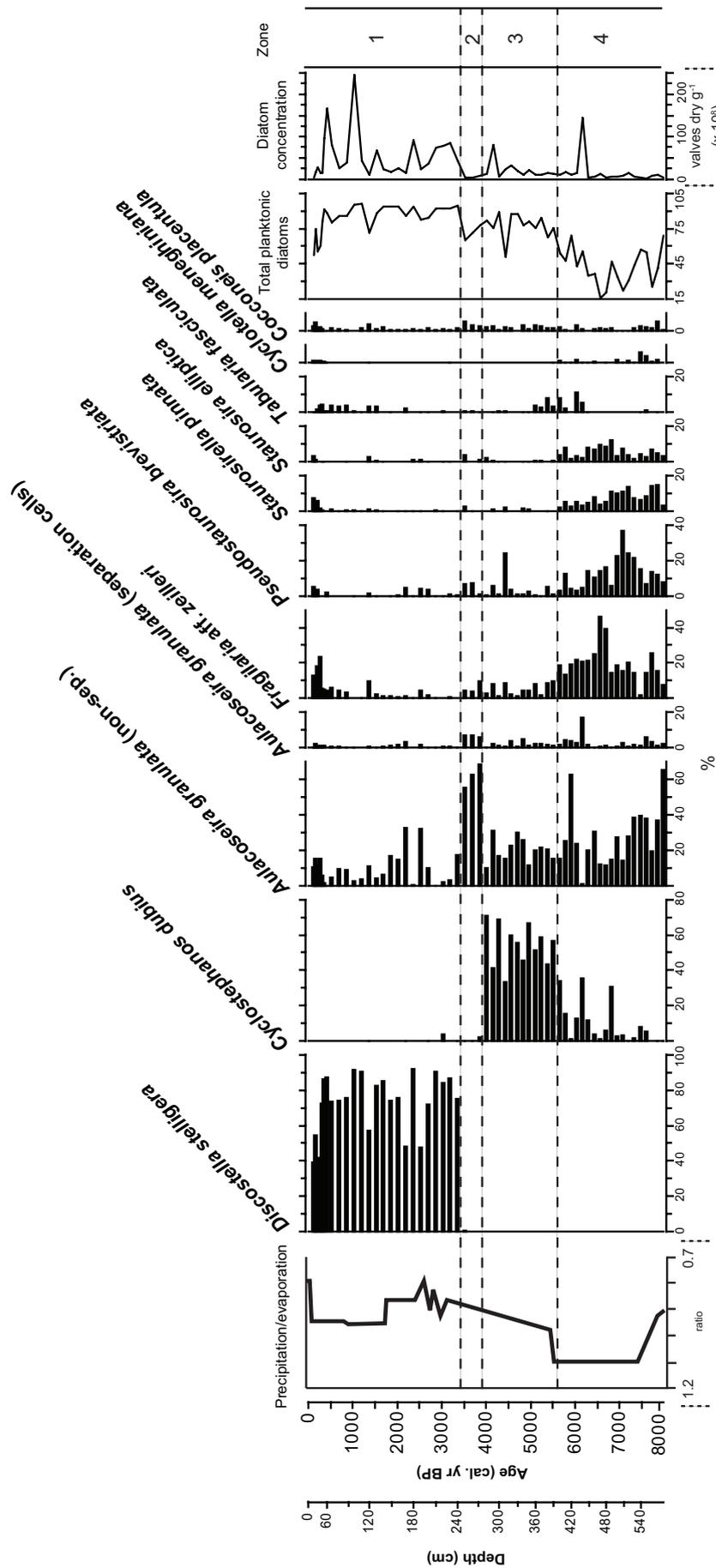
Figure 2. Diatom stratigraphy, total proportion of planktonic taxa and diatom concentration from the Lake Purrumbete Mackereth core. Only taxa with a relative abundance >5% in at least one sample were included. The inferred precipitation/evaporation (P/E) ratio derived by Jones et al. (1998) from western Victorian palaeoenvironmental data is also shown. The P/E ratio illustrated is the lower estimate of the range illustrated in Jones et al. (1998) non-sep. = the non-separation cells.

generated mixing during this time.

For approximately the past 3500 years, the diatom community in Lake Purrumbete has been dominated by *Discostella stelligera*, a freshwater planktonic species that, in high relative abundances such as observed in the Lake Purrumbete record, is indicative of oligotrophic waters (see Tibby 2004 and references therein). *Discostella stelligera*, which has a total phosphorus optimum of 16 µg l^{-1}, dominates the record at a time of substantial climatic variability and persists through relatively arid and relatively wet phases during which, for example, trees grew at the edges of lakes Keilambete and Bullenmerri and were subsequently drowned approximately 2000 years ago (Bowler 1981). Indeed, the period from 3100 cal BP to 2000 cal BP is one of substantial climate variability in western Victoria, with two >5 m oscillations in the level of Lake Keilambete recorded during this time and with the inferred P/E of 0.78 at 2500 cal BP the lowest recorded since the early Holocene (Jones et al. 1998). However, apart from this period being largely coincidental with the onset of the *Discostella stelligera* dominance in the Lake Purrumbete record, there is little to differentiate it from the period of sustained higher moisture availability between 2000 cal BP and 110 cal BP where P/E reached 0.95 (see Figure 2). Arguably, *Cyclotella stelligera* may have been advantaged relative to *Cyclostephanos dubius* from 3100 cal BP to 2000 cal BP because the conditions which resulted in increased aridity (e.g. a reduction in winter storm tracks delivering moisture to the region) advantaged this smaller, less silicified taxon in a more stratified lake environment. The persistence of this taxon following this period (i.e. post 2000 cal BP), however, is less explicable, but it appears to highlight a degree of resistance to substantial climate variability.

Vegetation response to Holocene climate variability and European impact

In contrast to the dramatic changes apparent in the diatom record, the overriding characteristic of the Lake Purrumbete pollen record is one of stability though the greater part of the Holocene. All of the common dryland pollen types maintain, with some variability, their values over time. The Casuarinaceae are perhaps the only exception, with a decrease in relative abundance from around 4000 cal BP. The apparent stability of *Eucalyptus* and Chenopodiaceae pollen throughout this period does not appear to support soil salinisation as a likely cause of the decline in Casuarinaceae in our record (*sensu* Crowley 1994) and it is not clear whether the data presented here are in fact part of the broader decline in Casuarinaceae observed at a number of sites in the western Victorian Basaltic Province (see Kershaw et al. 2004). The muted vegetation response to the climatic changes known to have occurred in the area, and particularly to the relatively arid and variable climatic conditions centred around 3000-4000 BP (Bowler and Hamada, 1971; Bowler 1981; Chivas et al. 1985, 1986; Figure 3) which are shown here to have had dramatic implications for the freshwater ecology of Lake Purrumbete, is remarkable, and has been noted elsewhere (Dodson 1974, p. 716-717, 2001, Dodson et al. 2004). We conclude that the amplitude and/or duration of climatic variability during the Holocene did not exceed the resilience (*sensu* Holling 1973) of the sclerophyll woodland flora.

As with other vegetation records from western Victoria, the impact of non-indigenous land-use practices since the early part of the 19th century (from 32 cm depth in our record) is dramatic, reflecting the expansion of grasslands at the expense of woodland and forest, and the introduction of exotic plants. It is unclear what processes are driving the increase in *Myriophyllum* pollen during this period of European settlement. Gell et al. (1993), citing Orchard's (1985) seminal work on the genus, interpreted similar recent increases in *Myriophyllum* pollen as evidence of mass-flowering following stranding of *Myriophyllum* beds. Arguably, similar patterns at other lakes from the region (Tower Hill, main lake, zone ML1; D'Costa et al. 1989; Cobrico Crater, central core; Dodson et al. 2004) imply that recent changes in the aquatic flora are perhaps indicative of some regional phenomenon, rather than site-specific variability in
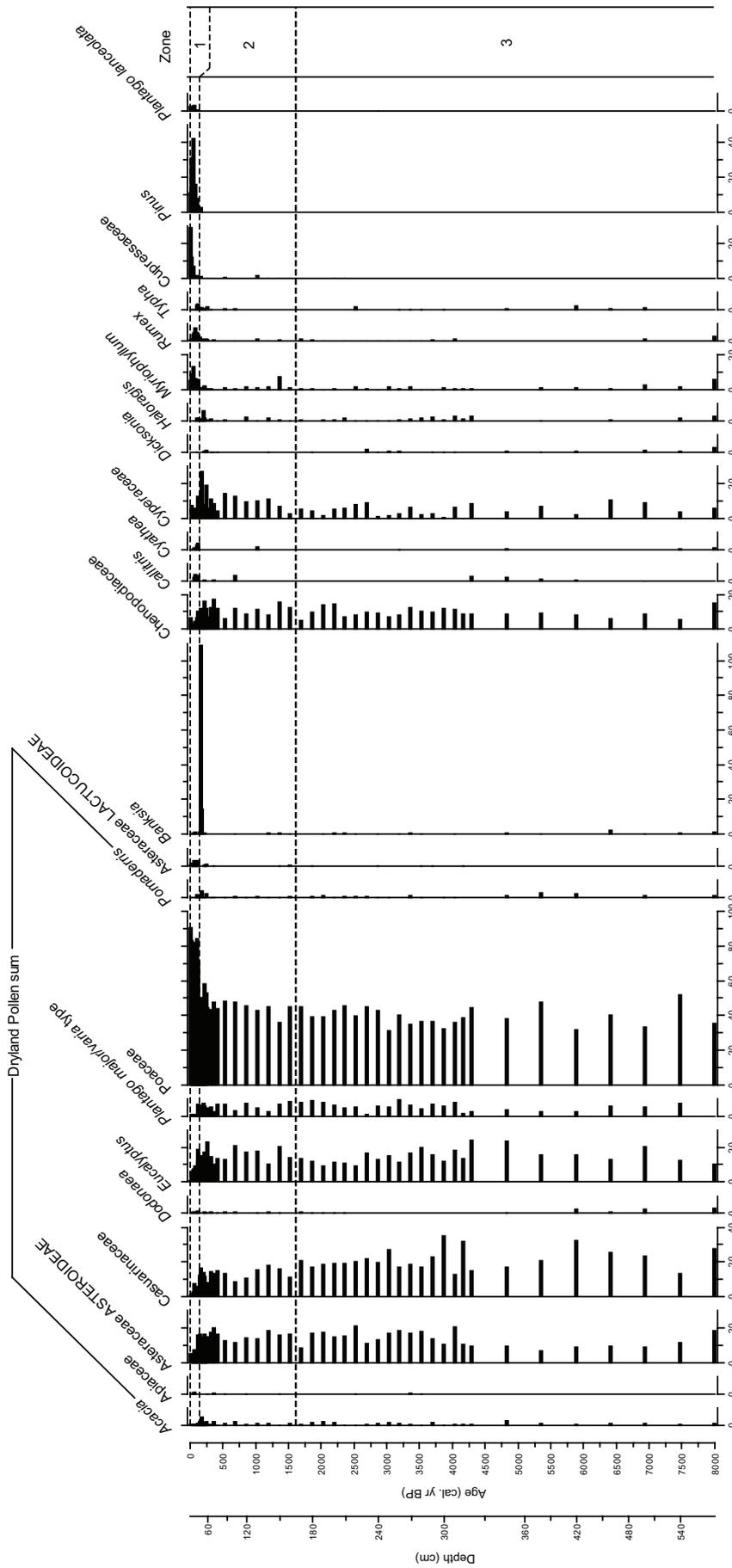
Figure 3. Pollen stratigraphy from the Lake Purrumbete core, showing variation in selected taxa against time. All taxa expressed as % relative abundance (see text). The upper 60 cm of the record is taken from a frozen spade core, and correlated to the longer Mackereth core using the first appearance of Pinus pollen as a biostratigraphic marker.

water levels.

Implications for understanding lake response to future climate change

In many Western District lakes, salinity concentrations are highly sensitive to climate (Kirono et al. 2009; Leahy et al. 2010) and recent climate-driven salinity increases have led to losses in biodiversity (Leahy et al. 2010). Future climate changes will further increase the loss of diversity in many western district Lakes. Although salinity in Lake Purrumbete is related to climate (Tibby and Tiller 2007, Yihdego 2010), modelled salinity increases over the coming decades are predicted to be moderate (Yihdego 2010) and not likely to result in large losses of diversity. Given the relative resilience of Lake Purrumbete to future climate driven salinity increases, factors such as macrophyte abundance and algal dynamics, which themselves are mediated by nutrient concentrations, are much more likely to be future drivers of diversity in Lake Purrumbete.

The Lake Purrumbete diatom record indicates that water quality, in particular nutrient status, can exhibit both marked sensitivity and apparent resilience to climate variation. The former is most amply demonstrated by the transition from dominance of a species associated with high nutrient concentrations, *Cyclostephanos dubius*, to *Discostella stelligera*, a taxon with markedly lower nutrient status. By contrast, resistance to environmental change is seen by the continued dominance of *Discostella stelligera* through lengthy periods of contrasting late-Holocene climate. Similarly, the palaeoenvironmental record shows that macrophytes like *Myriophyllum* have exhibited resilience over thousands of years, and then a late-Holocene rapid rise in abundance. This then provides lake managers with evidence that the rapid changes in *Myriophyllum* observed in the historical period have not occurred previously in the Holocene. In combination, these data suggest that while lakes such as Lake Purrumbete may 'resist' a degree of climate variability, when shifts do occur they are likely to be more abrupt, sustained and severe than can be predicted from even lengthy monitoring. From a lake-management perspective, climate-driven changes in mixing regime and nutrient cycling may propagate large and sudden changes in lake ecology. Hence, lake managers should give priority to reducing diffuse sources of nutrients to the lake to minimise the risks associated with changes in nutrient status.

Conclusion

The diatom record from Lake Purrumbete indicates that large lake systems can undergo rapid and sustained shifts in their water quality and ecology in response to climate change, even when lake levels show only minor alterations to climate perturbation (De Deckker 1982). Moreover, the limnological sensitivity of Lake Purrumbete to climatic variability is shown to be much greater than the catchment vegetation. It is clear that the limnology of Lake Purrumbete during the early to mid-Holocene was notably different to that of the late Holocene. Indeed, as with other lakes in the region, it appears that water-column nutrient concentrations in this lake were elevated, relative to the time of settlement, from 8000 to approximately 3500 years ago. As a result, the record of past environmental change in lakes such as this can provide an otherwise unobtainable insight into the behaviour of these systems.

Acknowledgements

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