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THEMATIC SET SHEMAX

Quantifying late Quaternary Australian rainfall seasonality changes using the Poaceae:Asteraceae pollen ratio

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Abstract

Mounting evidence suggests that the Southern Westerly Winds were significantly equatorially displaced and more intense during the last glacial maximum (LGM), prompting deliberate research identifying proxies to reconstruct these changes. This has focused on rainfall seasonality to track changes in major circulation patterns across the southern hemisphere mid-latitude regions. Using a common methodology to reconstruct climatic changes aids comparability and makes it easier to draw significant conclusions regarding general circulation movements. We assess the applicability of Coetzee's (1967) Poaceae: Asteraceae pollen ratio, which has been used successfully in South Africa, in the Australian context. The ratio scores from modern samples fail to capture the weak seasonality in the southeast and on Tasmania but is successful for the rest of the continent. The periods of greatest change compared to present day match known periods of distinct climatic events, namely the mid-Holocene (6–7 cal ka BP), the last deglacial period (15–17 cal ka BP), and two periods during the LGM (20–22 and 31–33 cal ka BP), suggesting large parts of Australia experienced a "double peak" of rainfall seasonality change during the LGM. This confirms that the Poaceae:Asteraceae pollen ratio can be used on records outside of South Africa.

Keywords: Rainfall seasonality; Southern Westerly Winds; Last Glacial Maximum; Pollen; Southern Hemisphere; Quantitative

INTRODUCTION

Australian rainfall is highly variable, due to the influence of multiple large-scale climate systems (Sturman and Tapper, 2006). This variability manifests itself not only in the distribution of rainfall, but also in its seasonality (Singh and Luly, 1991). In the north, a monsoonal climate is the dominant influence, with almost all the rainfall concentrated in the summer months (Suppiah, 1992). The El Niño Southern Oscillation has a strong influence on the rainfall patterns over much of the continent, particularly in the northern and eastern parts, but its influence is not constrained to a particular season (Risbey et al., 2009). Rainfall patterns in the south are strongly affected by the Southern Westerly Winds (Fletcher and Moreno, 2012), especially the western coasts, leading to most of the precipitation falling there during the winter months. The interior of the continent is extremely dry, with large parts receiving less than 200 mm of rainfall annually (Nicholls et al., 1997).

Rainfall seasonality is highly spatially and temporally heterogeneous, as synoptic-scale climate systems, including the westerly winds, change in strength and location, influenced by factors such as the extent of sea ice in the Antarctic and the meridional temperature gradient (Sturman and Tapper, 2006). Monsoons determine summer rainfall for much of the world's tropics; they are influenced by the Hadley Cell circulation, which varies in strength and location according to changes in sea surface temperature and is stronger during the summer months when sea surface temperatures are highest, leading to more moisture in the air (Colls and Whitaker, 2012). Examining past rainfall seasonality patterns for Australia allows for these synoptic systems and their evolution to be reconstructed. Singh and Luly (1991) examined an 18,000-year-long pollen record from Lake Frome in South Australia and found evidence for several past changes in rainfall seasonality, including a prolonged period of southerly displacement or expansion of the monsoonal belt between about 13,000 and 4500 yr BP. Before this the record showed evidence of increased winter precipitation, and after 4500 yr

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BP the lake reached its ephemeral state, only filling during periods of monsoonal incursions (Singh and Luly, 1991). This qualitative study inferring rainfall seasonality on the basis of presence or absence of certain plant taxa highlights the fact that the Australian flora and its distribution is affected not only by the amount of rainfall it receives, but also by the time of year that this rain falls. This is supported by a quantitative study by Fletcher and Thomas (2007), which demonstrated that it is possible to infer rainfall seasonality in Tasmania from assemblages of modern moorland pollen.

Australia spans a similar latitudinal range to that of South Africa, encompassing both the subtropics and midlatitudes (Braganza et al., 2015). South Africa is therefore similarly characterised by summer, winter, and year-round rainfall regimes (Roffe et al., 2019). There has been considerable effort in South African palaeoclimate science to quantify the changes in rainfall seasonality of the late Quaternary, as this has significant implications regarding firstly the veracity of palaeogeomorphological evidence for niche glaciation in the eastern Lesotho highlands, and secondly the use of the landscape by Stone Age communities (Fitchett et al., 2016a; Fitchett, Grab, et al., 2017; Stewart and Mitchell, 2018). The evidence for niche glaciation suggests that the winter rainfall zone may have extended as far north as Lesotho, but this same evidence requires additional proxies to validate these interpretations (Mills et al., 2012). The most common approach has been the identification of Fynbos species in the pollen record (Scott, 1989; Scott, 2002; Neumann et al., 2014). As the Fynbos are endemic to the Cape Floristic Zone, a biome situated in the southwestern corner of the African continent, which has undisputedly remained in the winter rainfall zone throughout the late Quaternary (Meadows and Sugden, 1993), this provides strong evidence for the expansion of winter rainfall conditions. However, this approach is limited in that it precludes any reconstruction of seasonality in pollen records that do not contain Fynbos elements. It would also, necessarily, prevent comparison with records outside of South Africa, such as those from Australia.

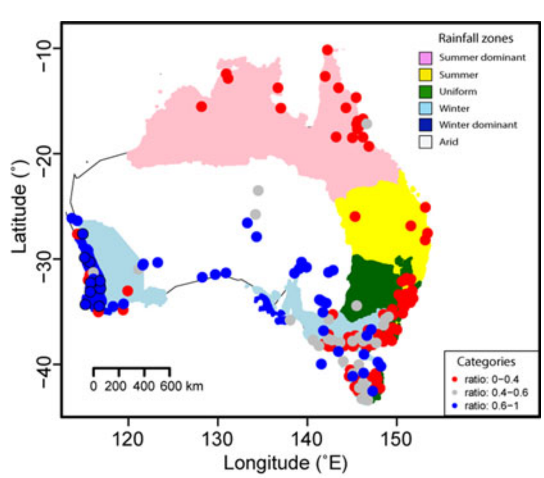

Figure 1. (color online) Observed modern rainfall zones, adapted from the Bureau of Meteorology (2005) with modern ratio values plotted by site; red indicates that summer rainfall is dominant, grey that there is no dominant seasonality, and blue that winter rainfall is dominant.

A method of seasonality reconstruction that involves more cosmopolitan taxa is therefore of value. Coetzee (1967) proposed the use of the ratio of Poaceae:Asteraceae fossil pollen to quantify rainfall seasonality for Eastern and Southern Africa (Poaceae is the family of grasses and Asteraceae is the family of daisies). The ratio has subsequently been used for a number of sites across southern Africa (Scott and Nyakale, 2002; Norström et al., 2009, 2014; Fitchett et al., 2016b; Fitchett, Mackay, et al., 2017). More recently, a deliberate attempt has been made to determine the validity of this ratio in effectively discriminating between the winter and summer rainfall zones (Fitchett and Bamford, 2017). The ratio was found to be statistically effective; the botanical mechanism was hypothesised to involve a combination of a lower proportion of Asteraceae species in the summer rainfall zone where conditions favour grass, greater grass pollen production in the summer rainfall zone, and poor Asteraceae pollen preservation in this region.

As these are cosmopolitan species, the efficacy of this ratio should, arguably, extend to other countries within the same latitudinal range that are similarly characterised by both summer and winter rainfall zones. Consequently, we apply this ratio to Australia, with the aim to determine (1) whether the ratio is effective in quantifying rainfall seasonality for Australia, (2) late Quaternary shifts in the location of the winter rainfall zone in Australia as reconstructed from this pollen ratio, and (3) the coherence in this shift across the Southern Hemisphere.

METHODS

As this study attempts to apply the Poaceae:Asteraceae pollen ratio used in South Africa to the Australian context, the methods outlined by Coetzee (1967) in calculation of the ratio and those of Fitchett and Bamford (2017) in performing comparative analyses are used without modification. However, the dataset identification, data collection, standardisation, and quality checking are unique to this study.

We use an existing database of Australian pollen samples (Herbert and Harrison, 2016), which has standardised the chronologies of all the records, updating the calibrations to SHCal13 and using Bacon v.2.3 in R to calculate

Table 1. Percentage of agreement between modern ratio scores and observations.

Zone	Sites agreeing (%)	Sites disagreeing (%)
Summer dominant	100	0
Summer	100	0
Year-round	22	78
Winter	20	80
Winter dominant	86	14

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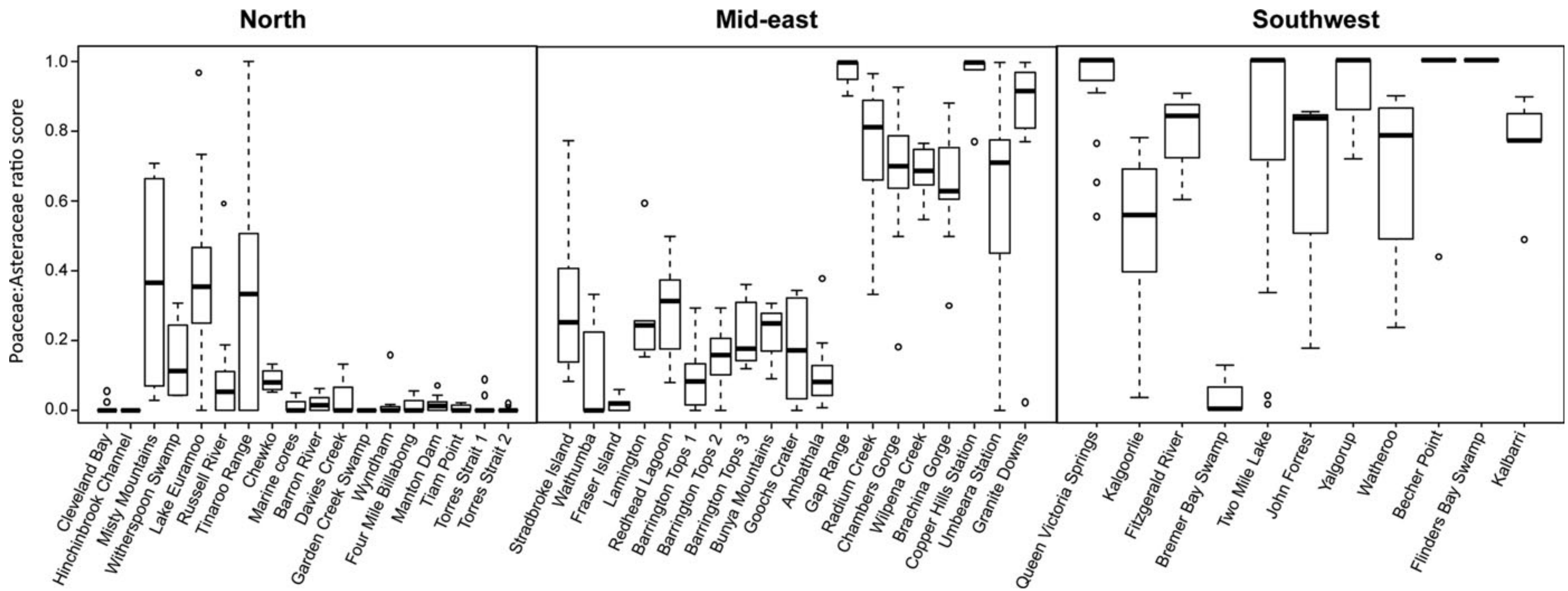

Figure 2. Boxplots for the Poaceae:Asteraceae ratio scores from all sites in the north, mid-east, and southwest, separated by region and arranged east to west.

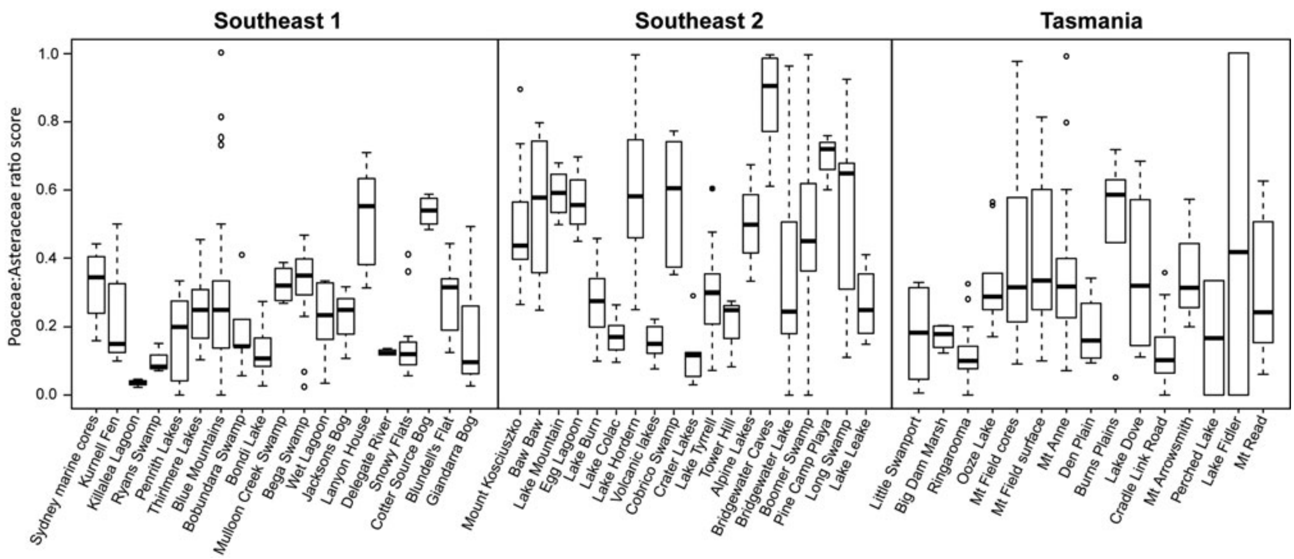

Figure 3. Boxplots for the Poaceae:Asteraceae ratio scores from all sites in the southeast and Tasmania, separated by region and arranged east to west.

the age models, taking into consideration any published age models. This database was compiled from published and unpublished pollen records, many of which represent pollen samples and cores that were collected as far back as the 1960s. Some of these records have been superseded by more recent collections, but others have been retained as they provide important coverage in areas otherwise lacking records. The pollen sums were standardised after extraction from the database, with all sample counts converted to percentages after removal of local taxa such as aquatics, mosses, obligate halophytes, parasitic plants, agricultural crops, and mangroves. Any samples containing five taxa or fewer and/or dominated (>75%) by a single taxon were removed.

Rainfall seasonality here follows the definition and main categories used by the Australian Bureau of Meteorology (BoM), based on the median rainfall of the 100-year period 1900–1999. BoM identifies six major rainfall zones in Australia, namely (1) summer dominant (marked wet summer and dry winter), (2) summer (wet summer and low winter rainfall), (3) uniform (year-round rainfall), (4) winter (wet winter and low summer rainfall), (5) winter dominant (marked wet winter and dry summer), and (6) arid (low rainfall). These categories are defined based on median annual rainfall and seasonal incidence, where the seasonal incidence is the ratio of the median rainfall over the period November–April to the period May–October (see Supplementary data).

To aid interpretation, the sites have been divided into regions broadly correlating to the modern rainfall zones. These regions and their modern rainfall seasonality are:

a) North: north of 20° S. Summer rainfall is dominant.
b) Southwest: south of 20° S, west of 140° E. Winter rainfall is dominant, but becomes less so further east.
c) Mid-east: 20°–33.5° S, east of 133° E. Summer rainfall near the coast, transitions to year-round rainfall further west.
d) Southeast: 33.5°–40° S, east of 140° E. Year-round rainfall by the coast, transitions to winter rainfall further west.
e) Tasmania: year-round rainfall in the southeast, winter rainfall for the rest of the island.

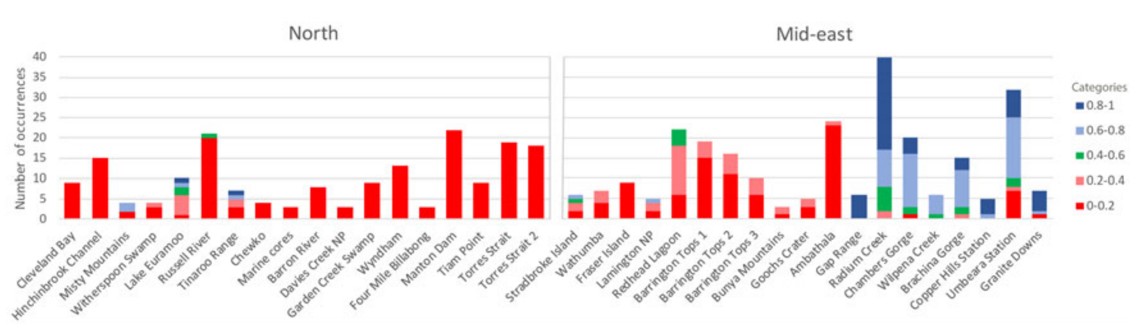

Figure 4. (color online) Frequency distributions for the ratio scores for sites in the north and mid-east.

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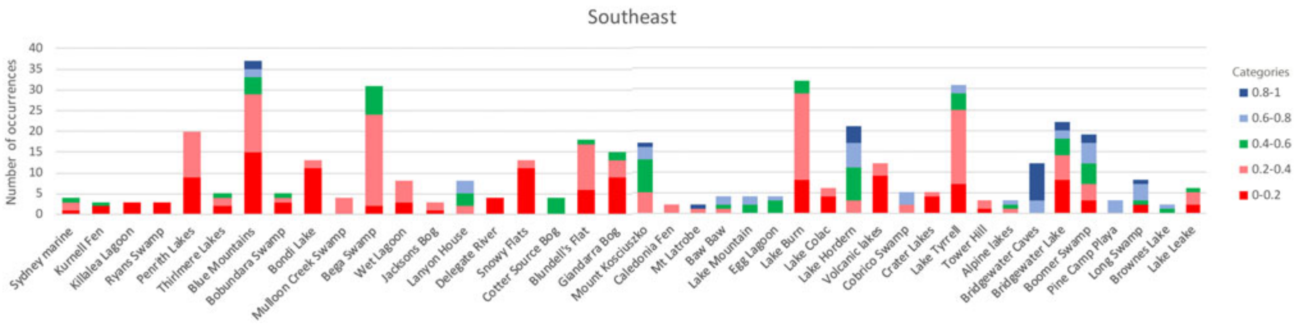

Figure 5. (color online) Frequency distributions for the ratio scores for sites in the southeast.

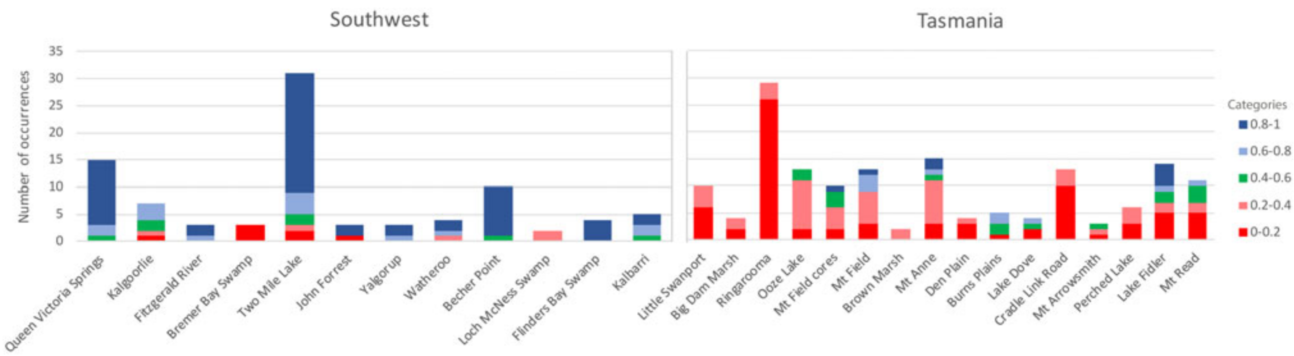

Figure 6. (color online) Frequency distributions for the ratio scores for sites in the southwest and Tasmania.

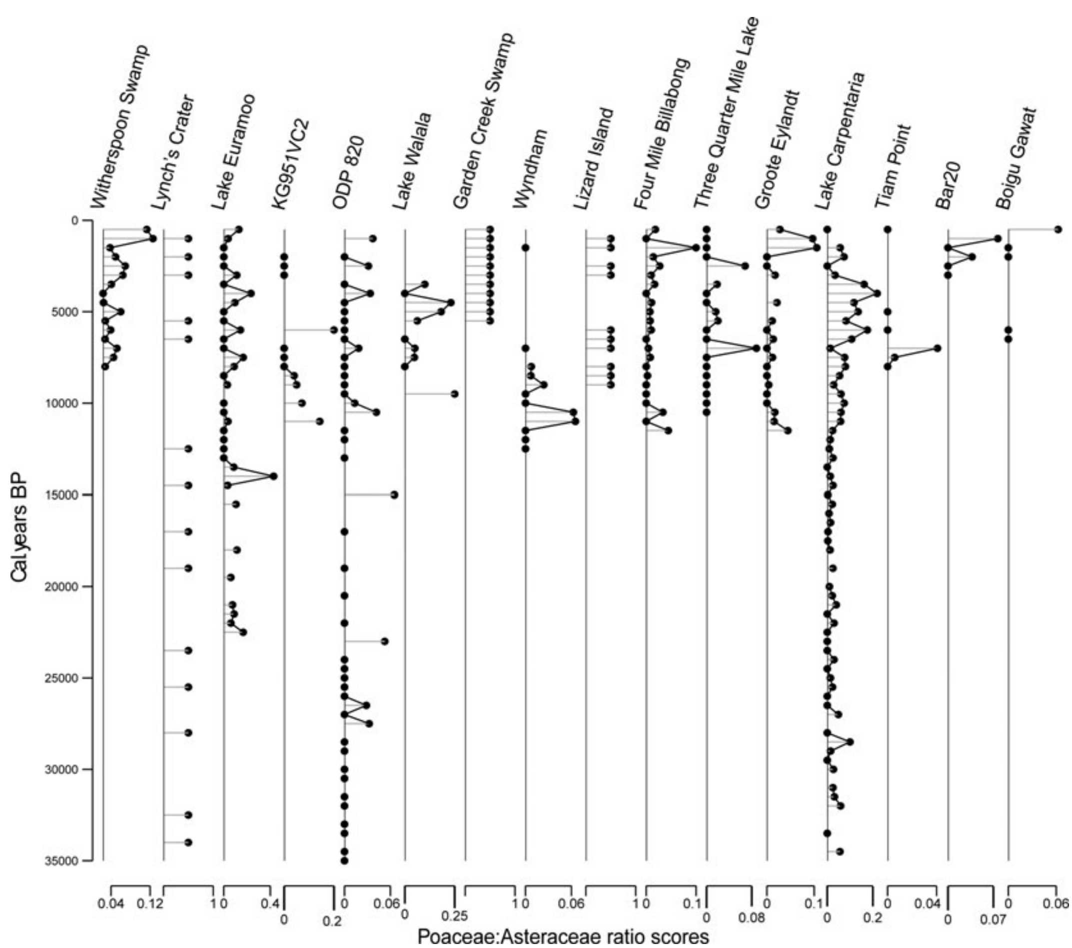

Figure 7. Stratigraphic plot of the 500-year mean fossil Poaceae:Asteraceae ratio scores for all records from sites in the north.

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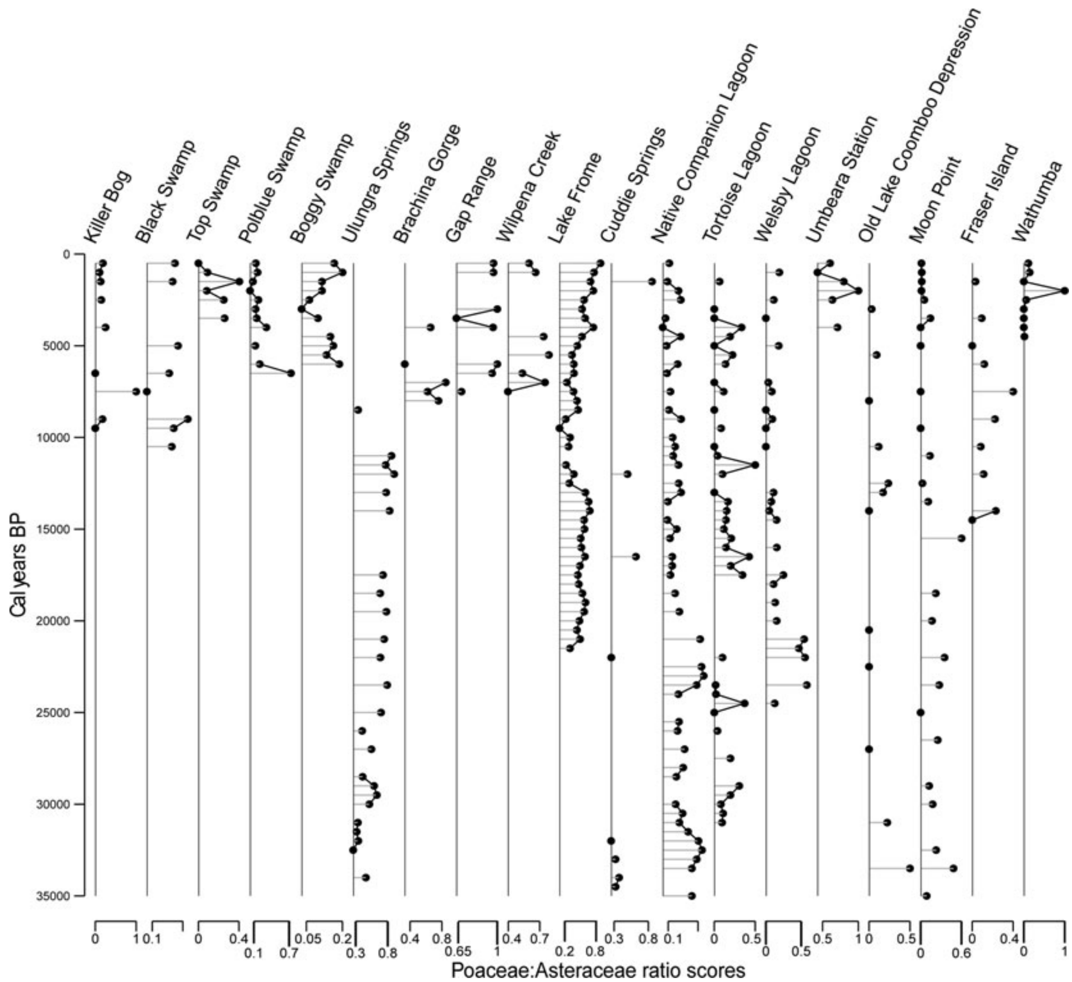

Figure 8. Stratigraphic plot of the 500-year mean fossil Poaceae:Asteraceae ratio scores for all records from the mid-East.

RESULTS

Modern rainfall zones

In order to establish whether the Australian flora responds to changes in rainfall seasonality in such a way that it is discernible from the ratio of Poaceae and Asteraceae pollen, the modern ratio scores are first examined in detail. If it can be determined that the ratio scores from the modern samples fall within the ranges expected for their respective observed modern rainfall zone, this means that the Australian flora does respond to changes in rainfall seasonality and fossil samples can be used to reconstruct past seasonality changes through the use of this ratio.

From Figure 1 it is clear that modern Poaceae:Asteraceae ratio scores generally capture the regional rainfall seasonality well, with all sites from the summer rainfall zones indicating a ratio value in the range expected from areas where summer rainfall is dominant (0–0.4; Fitchett and Bamford, 2017). Most sites in the southwest similarly capture the dominant winter rainfall in this area (ratio scores 0.6–1; Table 1). The year-round rainfall in the southeast, however, has not been captured by the pollen samples, overwhelmingly showing values in the summer rainfall range. This is also the case for much of the Victorian coast in the winter rainfall zone, where many records indicate ratio scores in the summer rainfall or aseasonal range. A complicated picture emerges for Tasmania, with only a couple of sites correctly capturing the year-round rainfall of their area, most indicating summer rainfall, even in the winter rainfall zone. Possible reasons for this will be explored in the discussion section. All sites in the summer rainfall zones and most sites in the winter dominant rainfall zone capture the observed rainfall seasonality signal, whereas less than a quarter of sites in the year-round and winter rainfall zones capture the signal of their observed rainfall zones (Table 1).

Australian rainfall zones are not uniformly distributed (Fig. 1); rainfall seasonality is generally more distinct along the coasts and becomes less and less clear further inland until the arid interior is reached, which cannot be assigned to zones due to the low amount of rainfall. For instance, all sites closer to the coast in the mid-east suggest they are in the summer rainfall zone, with the sudden change to winter seasonality implied by the sites on the right-hand side of Figure 2 actually indicating the change to an arid climate, as the sites are arranged from east to west. For the north

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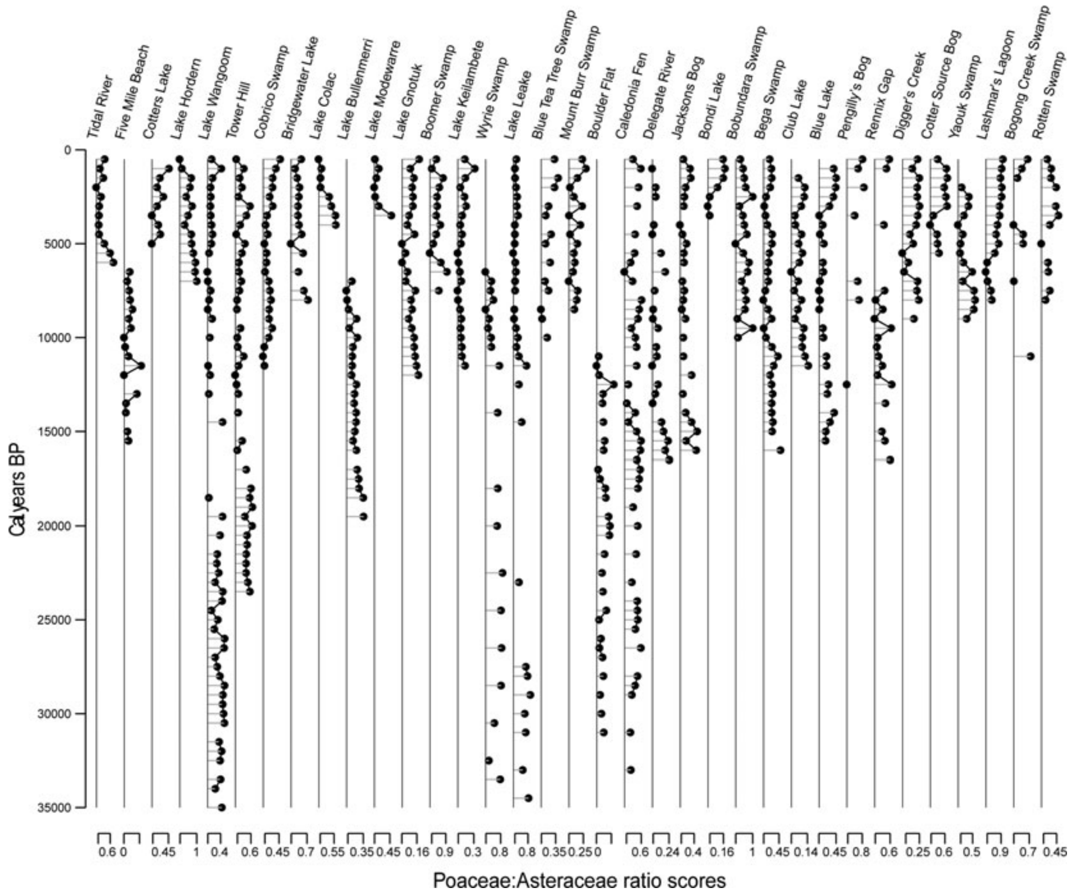

Figure 9. Stratigraphic plot of the 500-year mean fossil Poaceae:Asteraceae ratio scores for the first group of records from the southeast. The groups are arranged east to west and split evenly along this gradient for plotting purposes.

this arrangement also means that these sites are more or less arranged from south to north, which is why this subplot indicates an increase in summer seasonality from left to right, going into a monsoon-dominated climate in the far north. Almost all sites in the southwest boxplot correctly show ratio scores in the winter rainfall range. The two subplots for the southeast generally show an increase in the ratio scores from left (east) to right (west), with some exceptions (Fig. 3), matching the observed change from year-round or summer to winter rainfall (Fig. 1). The high inter-sample variability in the Tasmanian records is evident in the last subplot (Fig. 3). The area with the lowest inter-sample variability appears to be the north, as seen in the frequency plots in Figures 4–6. Most sites in the north contain samples that only produce ratio scores in the summer rainfall range (Fig. 4). The areas with the highest inter-sample variability are Tasmania and the southeast (Figs. 5–6). The reasons for this will be examined in the discussion section.

Fossil pollen ratio scores

Figure 7 suggests that the northern parts of Australia have remained in the summer rainfall zone for the past 35 ka, but there may have been some variations in the intensity of this seasonality. This may have been less intense at around 3–4 cal ka BP, 7 cal ka BP, and 22 cal ka BP. In addition, Lake Euramoo shows a brief change to year-round rainfall at 14 cal ka BP. The mid-east and Tasmania both show possible changes in seasonality at around 8–9 cal ka BP (Figs. 8 and 11), with Tasmania displaying a near millennial variability in rainfall seasonality between 9 and 12 cal ka BP. The southeast (Figs. 9–10) exhibits a change in seasonality around 11 cal ka BP, with some sites showing this change a bit later at ∼10 cal ka BP (e.g., Warrananga Salt Lake and Pine Camp Playa). There also appears to be a change to winter rainfall seasonality at about 25 cal ka BP (Fig. 10).

Figures 12 and 13 focus on the period 15–35 cal ka BP, and some movements of rainfall zones are discernible. The subplot for 16–16.9 cal ka BP (Fig. 12) shows a possible expansion of the winter rainfall zone further to the east and north than present day, with other periods of possible northerly and easterly expansion of the winter rainfall zone being 24–25 and 28–29 cal ka BP, the latter also seeing an expansion of the year-round rainfall zone.

The periods demonstrating the greatest differences in rainfall seasonality compared to present day include the mid-Holocene (6–7 cal ka BP), the last deglacial period (15–17 cal ka BP), and the last glacial maximum, split into

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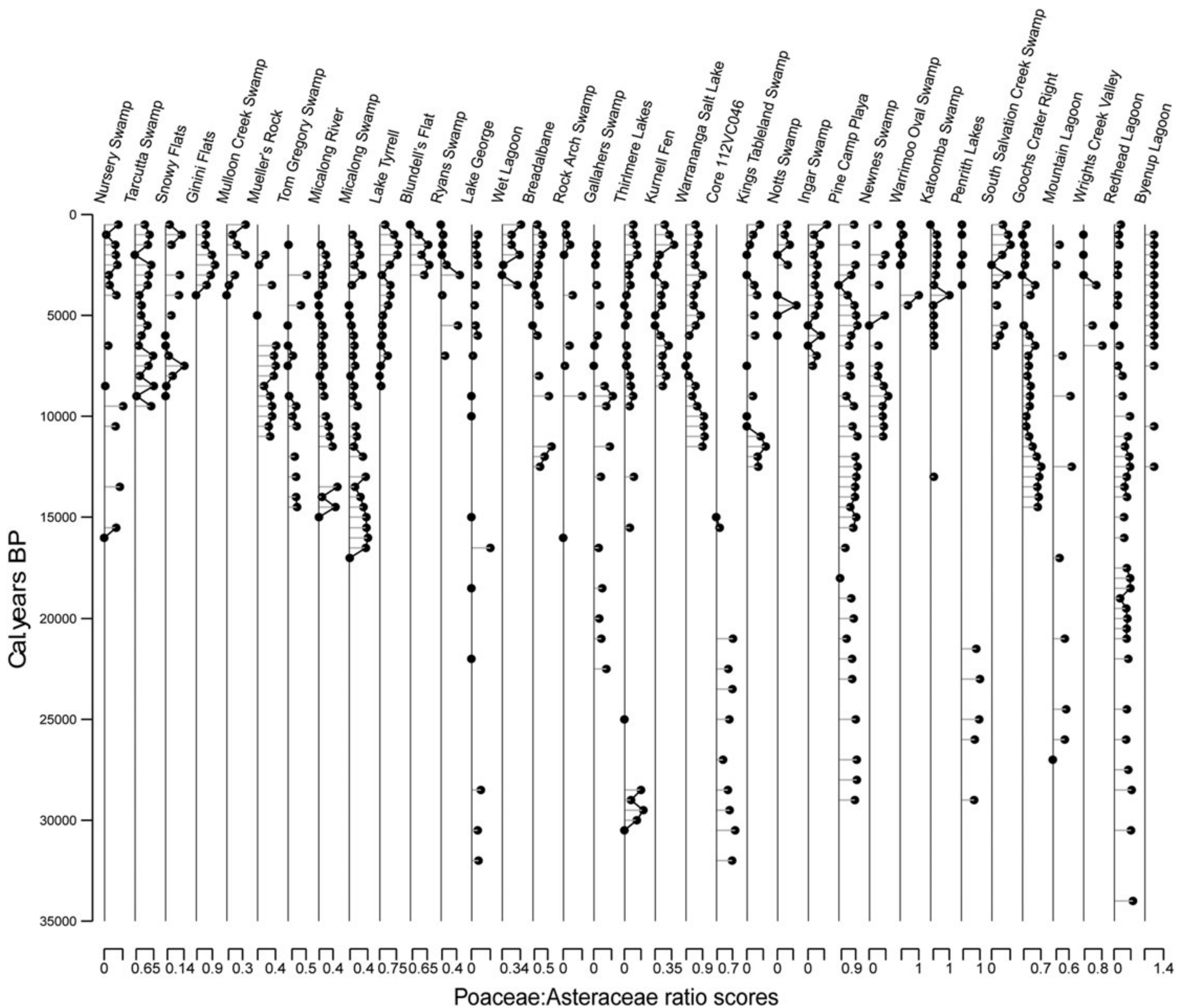

Figure 10. Stratigraphic plot of the 500-year mean fossil Poaceae:Asteraceae ratio scores for the second group of records from the southeast. The groups are arranged east to west and split evenly along this gradient for plotting purposes.

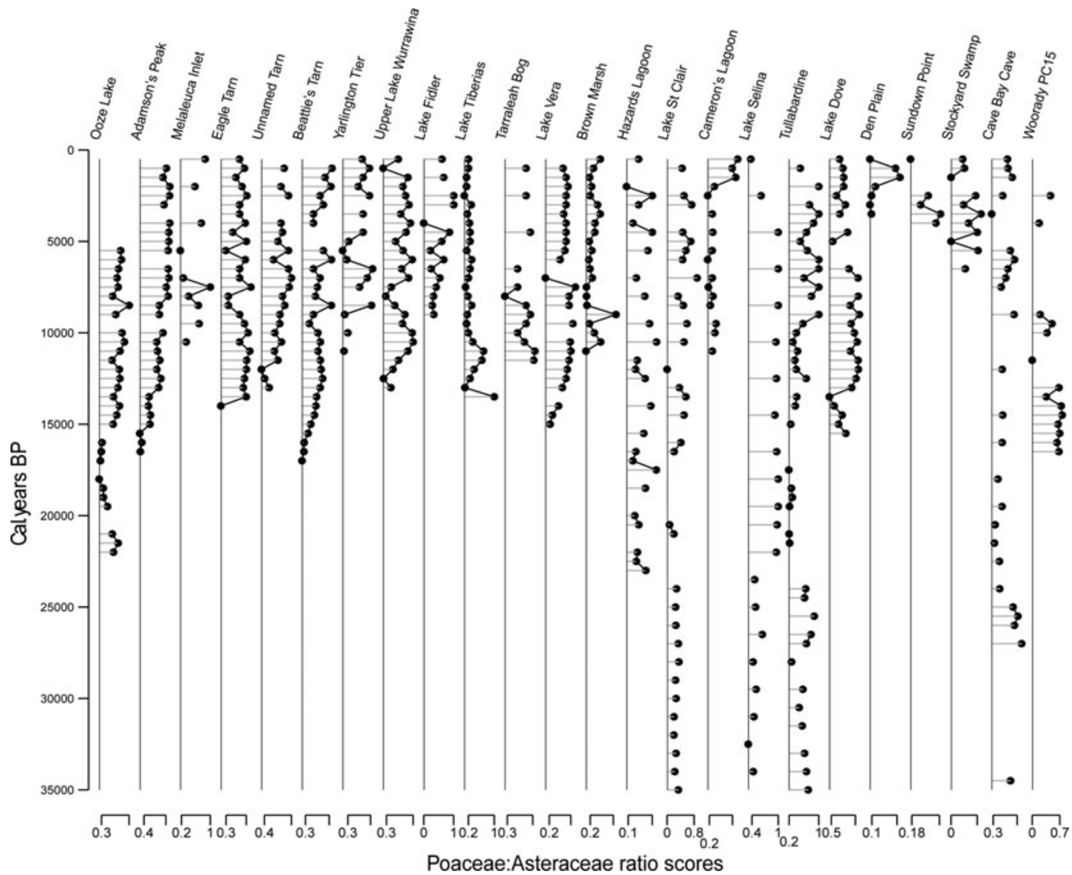

Figure 11. Stratigraphic plot of the 500-year mean fossil Poaceae:Asteraceae ratio scores for all records from Tasmania.

two peaks (20–22 cal ka BP and 31–33 cal ka BP). The period displaying the greatest difference compared to present day is 31–32 cal ka BP (Fig. 14).

DISCUSSION

Applicability of the Poaceae:Asteraceae ratio in Australia

There is generally large agreement between the rainfall seasonality reconstructed from the Poaceae:Asteraceae ratio scores and the observed contemporary rainfall seasonality for Australia (Fig.1, Table 1). The greatest disparities are in the southeast and Tasmania, due to the high inter-sample variability in these areas (Figs. 5–6), which in turn could be due to the lack of clear dominance in seasonality since they are characterized by either year-round or weakly winter dominant rainfall (Fig. 1). Interannual rainfall variability may therefore also come into play, especially as some of the pollen samples were collected decades apart. The mountainous locations of most of the sites in Tasmania could be another possible cause for the variability in this region; local effects such as rainfall shadows likely have an impact on the flora, which can change drastically within a very short distance, depending on the aspect of the slope (Burrows, 1961).

Temperature is another key factor to consider here, with parts of Tasmania and the southeast being classified as alpine areas, meaning they are above the natural tree line of the region. The vegetation in these areas is therefore dominated by shrubs and grasses, with Asteraceae and Poaceae being the dominant families in alpine areas worldwide (Körner, 1995). Most importantly in the context of this study, the relationship between these two families may differ between alpine and non-alpine areas and may be more affected by temperature than by rainfall in alpine areas. Lastly, the variability in these highly sampled regions could be due to the different sample types used; some sites have both core tops and surface samples such as moss polsters or soil samples. A previous study showed that the types of samples used will have an impact on resulting climate reconstructions (Herbert and Harrison, 2016), meaning that there is a difference in the flora being captured by the different sample types. However, rainfall seasonality reconstructions using Poaceae pollen from nearly the same modern Tasmanian dataset have been determined to be able to capture modern climate signals in a previous study by Fletcher and Thomas (2007). In this study they found that samples with a "significant amount" of Poaceae pollen was one possible indicator of Eastern Moor vegetation, due to this vegetation type being dominant in the more seasonal and drier parts of the island, but that moderate amounts of Poaceae should not be used to make inferences due to its

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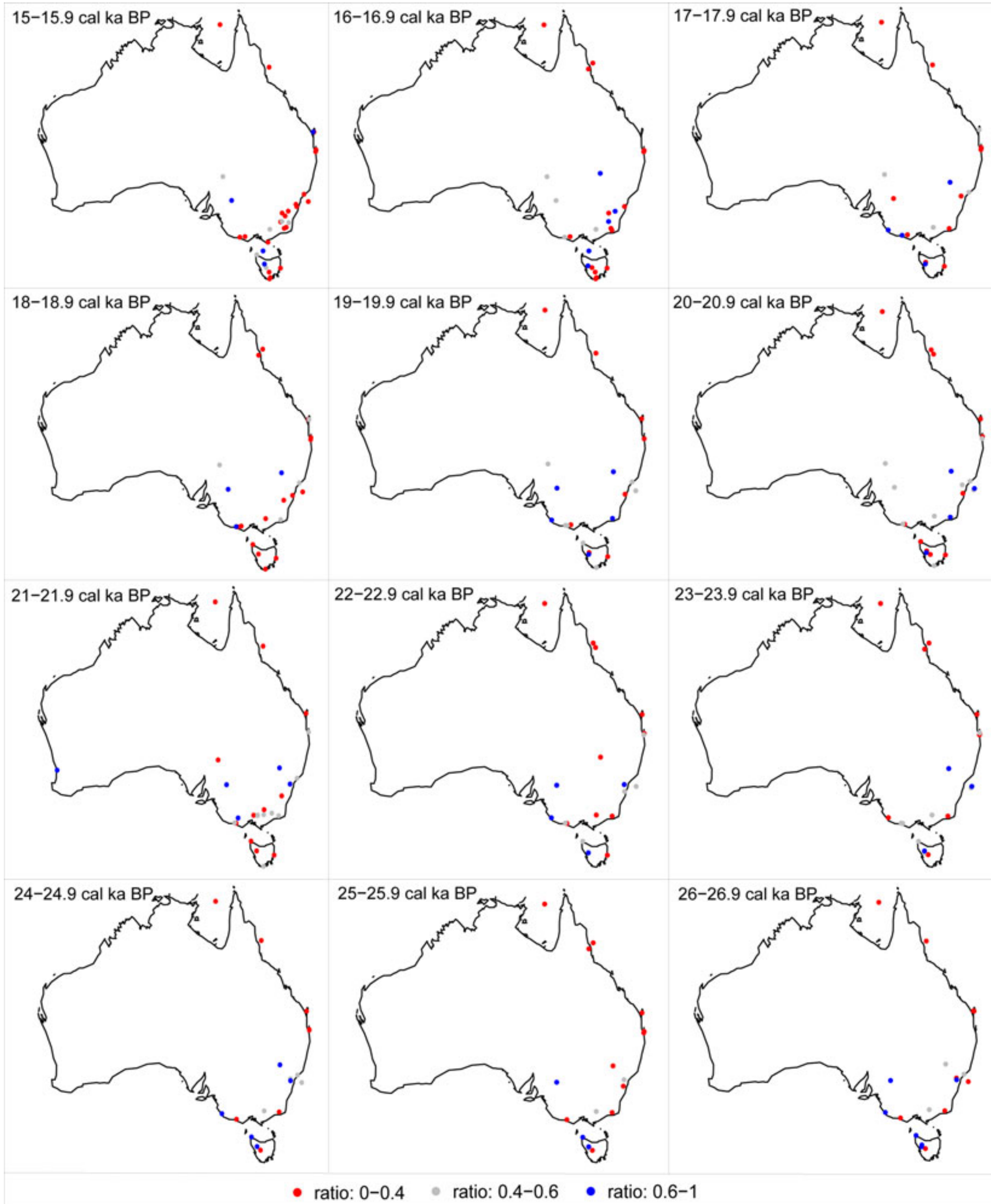

Figure 12. (color online) Maps of 1000-year mean Poaceae:Asteraceae ratio scores for each site, 15–26.9 cal ka BP.

over-representation (Dodson, 1983). The study also found that Asteraceae is another potential indicator taxon for this vegetation type, which could be another reason why our ratio had limited success in Tasmania, with both pollen types used in the ratio potentially indicating the presence of Eastern Moor vegetation. If high Poaceae values are used to indicate the winter rainfall zone of Tasmania instead of the Poaceae:Asteraceae ratio, the percentage of sites correctly identifying the winter rainfall zone (Table 1), jumps from 20 to 45, and the percentage of sites correctly identifying the uniform rainfall zone changes from 22 to 33. Despite this improvement, high values of Poaceae cannot be used to indicate winter rainfall in the past, as a reduction in overall precipitation may also lead to an increase in grasses, which is expected for at least parts of Tasmania during the last glacial maximum, for instance (Fletcher and Thomas, 2010).

Overall, the modern Poaceae:Asteraceae pollen ratio scores shows good agreement with the observed modern rainfall zones, indicating that this ratio has the potential to be used as a proxy for past changes in Australian rainfall seasonality. Even though this ratio has not been used to reconstruct Australian rainfall seasonality before, it has been used to determine alpine herbfield composition (Martin, 1986). Other pollen ratios have also been used on Australian records to determine vegetation types and thereby make climatic inferences, such as Poaceae: *Eucalyptus* (Martin, 1986;

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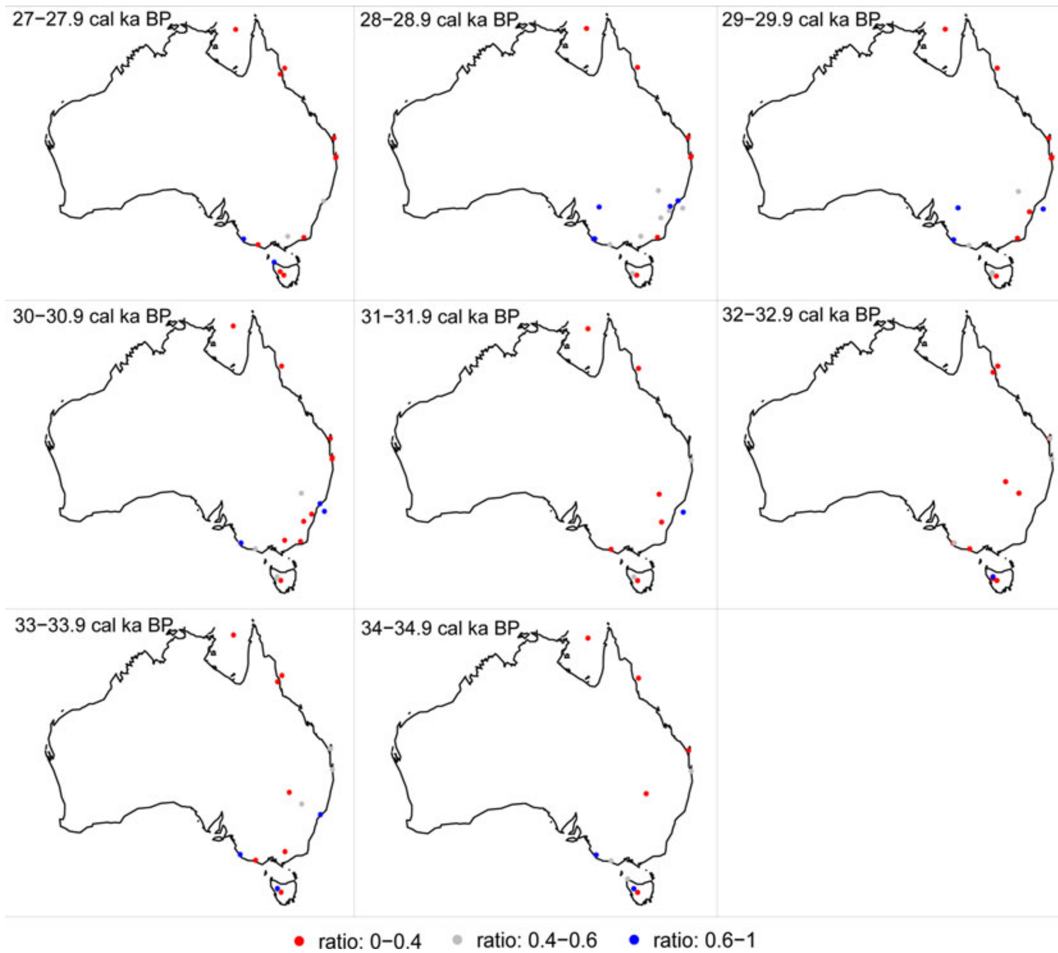

Figure 13. (color online) Maps of 1000-year mean Poaceae:Asteraceae ratio scores for each site, 27–34.9 cal ka BP.

Kirkpatrick and Fowler, 1998) and *Eucalyptus*: Chenopodiaceae (Martin, 1986). In addition, the ratio between Chenopodiaceae and Casuarinaceae has been used to determine levels of soil salinity (Crowley, 1994).

Reconstructed seasonality changes

There is a major change in the Lake Frome pollen record from year-round to summer rainfall seasonality at about 12.5 cal ka BP (Fig. 8). This was interpreted by Singh and Luly (1991) as evidence for a southern expansion of the monsoon belt, which is supported by evidence from northern Australia showing an intensification of the monsoon at this time (Ayliffe et al., 2013; Field et al., 2017). This period of monsoon incursion at Lake Frome seems to have continued until around 5 cal ka BP, which coincides with the period at which studies suggest there was an increase in the frequency of El Niño events (Fletcher et al., 2015), known to be linked to equatorward movements of the monsoon belt (Evans and Allan, 1992). However, if an expansion of the monsoonal belt was the cause, we would expect to see evidence of this from other records covering the same time period, along roughly the same latitudinal band. There may be a similar pattern in the Goochs Crater record in the southeast (Fig. 10), where the ratio score goes from the winter rainfall range to year-round at 12 cal ka BP, then to summer rainfall at 11 cal ka BP, where it persists until the present day. This is very unlikely to be linked to an expansion of the monsoonal belt, but it could be indicative of a weakening of the westerly wind system, which would affect the amount of winter rainfall received. A big enough decrease in winter rainfall might manifest itself as a change in rainfall seasonality. This is supported by a similar change discernible from Rennix Gap in the Snowy Mountains, as well as a later change at Wyrie Swamp by the Victorian coast. The lag in the Wyrie Swamp record could be due to its coastal and southerly location. A review of general vegetation changes in Australia during the Quaternary period by Dodson (1994) found evidence for a change in effective precipitation in southwestern Victoria and southeastern South Australia after about 12 ka, which could also be connected to this weakening of the westerly wind system.

The ratio scores in 1000-yr time windows for the period 15–35 cal ka BP are of significance with regards to efforts to reconstruct the last glacial maximum in the Southern Hemisphere in the context of the International Union for Quaternary Research project SHeMax (Petherick et al., 2016; Fitchett, Grab, et al., 2017), as it encompasses most of the

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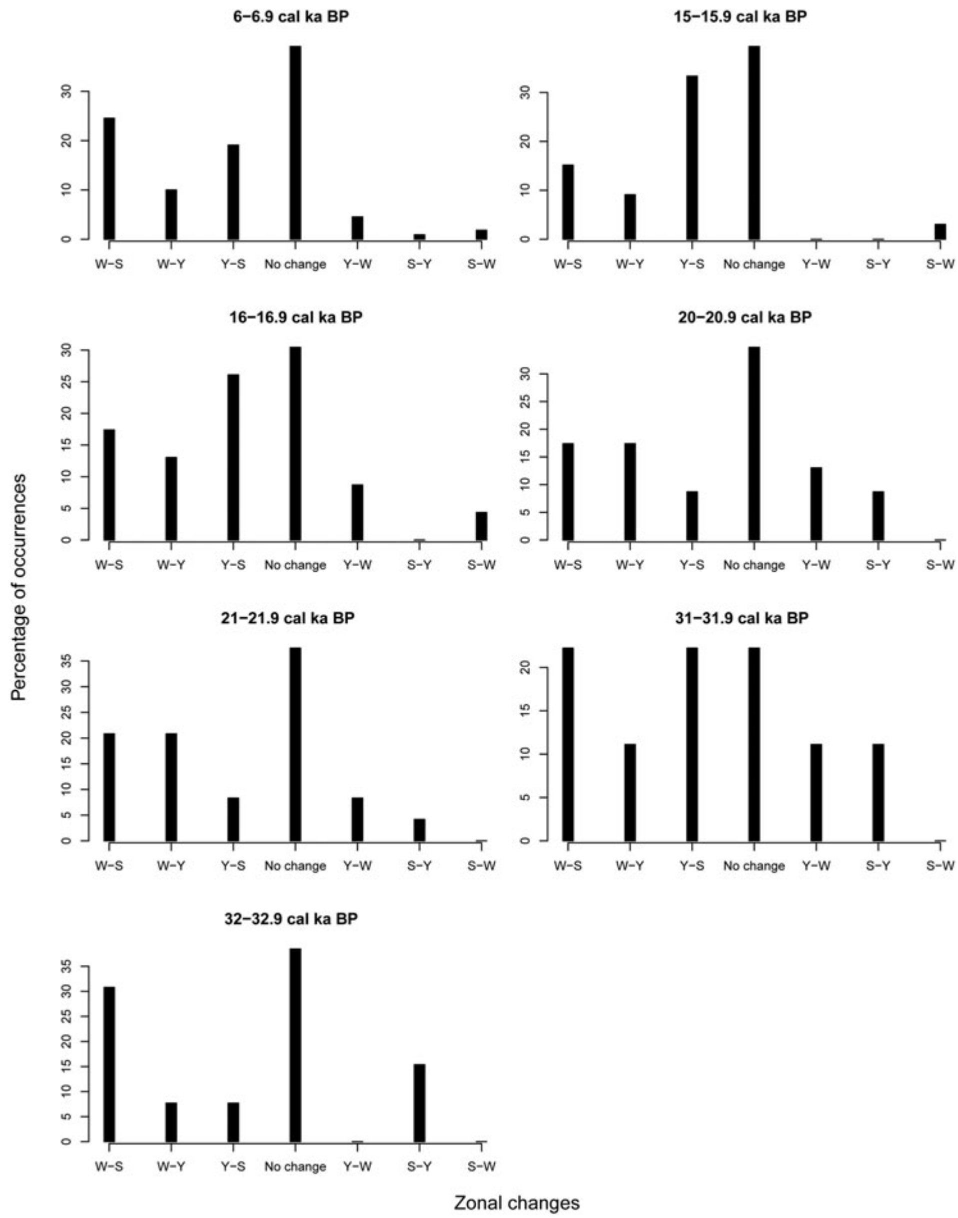

Figure 14. Frequency distributions of sites showing changes in rainfall seasonality compared to present day based on 1000-year means. Only time windows where less than 40% of the sites showed no change in seasonality are shown. W-S: change from winter rainfall today to summer rainfall; W-Y: change from winter rainfall today to year-round rainfall; Y-S: change from year-round rainfall today to summer rainfall; Y-W: change from year-round rainfall today to winter rainfall; S-Y: change from summer rainfall today to year-round rainfall; S-W: change from summer rainfall today to winter rainfall.

last deglacial period (~18–12 cal ka BP), the traditionally understood Last Glacial Maximum (LGM) period (~18–22 cal ka BP), and the possible early onset of the LGM in the Southern Hemisphere (30–35 cal ka BP; Petherick et al., 2016). From our maps (Figs. 12–13) it appears as if parts of this extended glacial period may have been marked by expansions of the winter and year-round rainfall zones. A possible easterly expansion of the winter rainfall zone may have occurred at 16 cal ka BP, with a possible northerly expansion at 24 cal ka BP, and a possible northerly expansion of both the year-round and winter rainfall zones at 28 cal ka BP. As both the last deglacial and glacial periods are known to have been rather different climatically compared to present-day conditions, these changes are expected and may be due to an expansion or northerly movement of the westerly wind belt (Kohfeld et al., 2013), but may also be due to a general decrease in available moisture, possibly with a greater decrease during the summer months. However, the idea of an extended winter rainfall zone during this time is supported by an extensive review of palaeo-records from parts of southern Africa (Chase and Meadows, 2007), an area likewise affected by the westerly wind belt along its western coast. Due to the lack of data from the western part of Australia, it is impossible to draw any conclusions

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regarding how the winter rainfall zone may have changed in this area during the last glacial maximum. According to the one record covering this time period from the southwest, winter rainfall was still dominant by the modern coastline 21–22 cal ka BP (Fig. 12).

The time windows displaying the greatest amount of change in rainfall seasonality compared to present day are highlighted in Figure 14; these are the mid-Holocene (6–7 cal ka BP), the last deglacial (15–17 cal ka BP), and two periods during the extended LGM, 10 ka apart. These last two periods, 20–22 cal ka BP and 31–33 cal ka BP, nearly perfectly match the two distinct cold, dry events found in the Native Companion Lagoon record (21.7 ka BP and 30.8 cal ka BP) by Petherick and colleagues (2008) and two glacial advances in the New Zealand records (31.5 ± 3 and 20.5 ± 2 ka (Alloway et al., 2007; Shulmeister et al., 2019). In the records presented here most of the change during these two events are changes from winter to summer rainfall zones (Fig. 14). This illustrates how big the changes in the temporal distribution of rainfall were during these times. The fact that the fossil Poaceae:Asteraceae ratio shows that the greatest changes in the Australian record as a whole were during these periods of known change is evidence that this ratio can be used successfully outside of South Africa.

Southern Hemisphere context

The weakening and poleward displacement of the westerly wind belt interpreted from the ratio scores of several sites in the southeast of Australia at around 11–12 cal ka BP has also been reported by several previous studies from South America. This suggests that the westerly winds were displaced poleward during the early Holocene (Jenny et al., 2003; Lamy et al., 2010; Razik et al., 2013), which is supported by records from the Southern Ocean suggesting a strong poleward displacement of the westerlies about 16–9 cal ka BP (McGlone et al., 2010).

For South Africa, this approach demonstrates a much later weakening and poleward displacement of the westerly belt at 4–5 cal ka BP (Fitchett and Bamford, 2017). This resulted in a significant contraction of the South African winter rainfall zone, consistent with the palaeogeomorphological record (Mills et al., 2012). Several records from southeast Australia support this, even though the change seems to have come slightly earlier to this part of the world, around 6 cal ka BP (Caledonia Fen, Boomer Swamp, Yaouk Swamp, and Tarcutta Swamp in Figs. 9–10). A similar study is yet to be conducted on South African samples older than 20 cal ka BP, so no conclusions regarding movements of the westerly wind system on a hemispheric scale can be made beyond this time.

CONCLUSION

This study shows that a Poaceae:Asteraceae pollen ratio can be used successfully to obtain a measure of rainfall seasonality for Australia going back thousands of years. With this ratio now being proven to work in both South Africa and Australia, the next step is to determine whether this is also the case for South America. As a region similarly affected by a monsoon system in the north and westerly winds in the south (Zhou and Lau, 1998), similar patterns could be expected to prevail when using the ratio. This would allow for a detailed analysis of the movements of the Southern Westerly Wind belt over several thousand years, which would in turn give an indication of how this vital system is likely to move during future climatic changes. However, some care needs to be taken in this mountainous region, as our results also suggest that high elevation sites may cause difficulties. Using the ratio in South America may therefore also highlight the reason behind these difficulties.

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SUPPLEMENTARY MATERIAL

The supplementary material for this article can be found at https://doi.org/10.1017/qua.2020.18.

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