A 23,000-yr pollen record from Lake Euramoo, Wet Tropics of NE Queensland, Australia

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Abstract

A new extended pollen and charcoal record is presented from Lake Euramoo, Wet Tropics World Heritage rainforest of northeast Queensland, Australia. The 8.4-m sediment core taken from the center of Lake Euramoo incorporates a complete record of vegetation change and fire history spanning the period from 23,000 cal yr B.P. to present. The pollen record is divided into five significant zones; 23,000–16,800 cal yr B.P., dry sclerophyll woodland; 16,800–8600 cal yr B.P., wet sclerophyll woodland with marginal rainforest in protected pockets; 8600–5000 cal yr B.P., warm temperate rainforest; 5000–70 cal yr B.P., dry subtropical rainforest; 70 cal yr B.P.–A.D 1999, degraded dry subtropical rainforest with increasing influence of invasive species and fire.

The process of rainforest development appears to be at least partly controlled by orbital forcing (precession), though more local environmental variables and human activity are also significant factors. This new record provides the opportunity to explore the relationship between fire, drought and rainforest dynamics in a significant World Heritage rainforest region.

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Keywords: Lake Euramoo; Pollen; Charcoal; Tropical rainforest; Holocene; Atherton Tablelands; Australia

Introduction

In 1970, the first pollen record from the Australian wet tropical rainforest (Lake Euramoo: Kershaw, 1970) was published and demonstrated that tropical palynology was indeed a viable approach to understanding rainforest dynamics over timescales only imagined in ecological studies. Since then, sediments from volcanic craters in the Atherton Tablelands of northeast Queensland have yielded multi-proxy data sets that have made an important contribution to our understanding of Australian palaeoclimates and rainforest vegetation history (Chen, 1988; Moss and Kershaw, 2000; Kershaw et al., 2002; Turney et al., 2004). One of the most outstanding attributes of these data is that they present a picture of a highly dynamic landscape, sensitive to both climate change and human activity on timescales ranging from millennia to decades (Haberle et al. in preparation; Turney et al., 2004).

The late Quaternary vegetation history of the Atherton Tablelands is characterized by the expansion of rainforest taxa during warm and wet interglacial periods and contraction of these same taxa, to as yet unknown refugial locations, during cool and dry glacial periods (Kershaw, 1994). The rate at which these changes take place and the nature of succession from one vegetation community to another has been examined in greatest detail over the late glacial transition. This period is represented in five pollen records from the Atherton Tablelands and shows that the transition from sclerophyll woodland to rainforest began as early as 11,500 cal yr B.P., took from 400 to 1000 yr to complete and was regionally concluded by 7000 cal yr B.P. (Hiscock and Kershaw, 1992). An increase in effective precipitation during the late glacial transition is considered the primary driver of vegetation change (Kershaw et al., 2002), though local factors including development of organic soils and fire frequencies (either natural or anthropogenic) may have contributed to the apparent inhibition of rainforest advance during the early Holocene.

Rainforest reach their maximum extent on the Atherton Tablelands by the around 7000 cal yr B.P. under a climate...
regime characterized by the establishment of modern day temperatures, possibly higher precipitation than present (or at least reduced seasonality in precipitation: Kershaw and Nix, 1988), and low frequency of fires (every 230 yr or so: Chen, 1988). Mid–Late Holocene rainforest composition was far from stable with high variability evident in rainforest pollen assemblages recorded during this period (Hiscock and Kershaw, 1992). Around 5000–6000 cal yr B.P. sustained rises in the emergent conifer *Agathis* and the early successional taxa Urticaceae/Moraceae, point to an opening up of the rainforest canopy perhaps due to reduced precipitation or increased disturbance. Rainforest disturbance may have had its origin in natural climate variability (El Niño-related storm and drought events: Gagan et al., 2004) or through increased intensity of human activity in rainforest environments (Haberle and David, 2004; Horsfall, 1987).

This paper describes a new core taken from the centre of Lake Euramoo in 1999, which is part of a study directed at understanding the origin and role of disturbance within tropical rainforests through fine resolution palaeoecology. The new core represents a complete record of sediment accumulation from the Last Glacial Maximum to the present (post-European period), which is unlike any other palaeoecological record from the Atherton Tablelands (Hiscock and Kershaw, 1992).

**The site**

Lake Euramoo is located near the western edge of the World Heritage Wet Tropics Bioregion of North East Queensland (718 m above sea level, 17º10’ S, 146º38’ E) on the Tertiary uplifted highlands of the Atherton Tablelands (Fig. 1) and within area that contains Australia’s most significant expanse of tropical rainforest. Lake Euramoo is a maar described as an ovate double explosion crater that formed during the Late Pleistocene period (Kershaw, 1970), with a relatively small catchment area of ~4500 m² and no inflow or outflow channels. The lake is warm monomictic with a water depth averaging around 20 m in the northern basin and 16 m in the southern basin, though there are seasonal fluctuations in water depth of between 2 and 3 m (Timms, 1976).

An annual average rainfall of 1500 mm is estimated to occur at Lake Euramoo with a distinctly dry winter rainfall regime as more than 60% falls between the months of January to March (Kershaw, 1970). The lake lies at the lower rainfall end of a steep east to west rainfall gradient. The dominant source of precipitation is the Southeast Trades interspersed with occasional Northwesterly monsoonal flows and associated tropical cyclones which also bring high but infrequent rainfall events during the austral summer months when the intertropical convergence zone (ITCZ) is at its most southerly extent (Godfred-Spenning and Reason, 2002). During El Niño episodes, a northward movement of the ITCZ and a northeasterward migration of the South Pacific convergence zone result in a significant decrease in summer precipitation (typically 150–300 mm below seasonal average) over the region (Dai and Wigley, 2000). Mean daily maximum and minimum temperatures are around 25.9º and 14.4ºC and frosts occur infrequently during the austral winter months at times of weak trade winds and low cloud cover.

The terrestrial vegetation surrounding Lake Euramoo is a remnant of moist sub-montane rainforest surrounded by previously cleared land that within the last 50 years has been either planted with endemic (*Araucaria cunninghamii*) and exotic conifers or has undergone secondary colonization towards re-establishing rainforest. Over 100 species of rainforest tree and shrub have been recorded within 100 m of Lake Euramoo (Kershaw personal communication). Typical moist sub-montane rainforest species found near Lake Euramoo include members of the Araliaceae (e.g., *Polyscias australiana*, *Schefflera actinophylla*), Araucariaceae (e.g., *Agathis robusta*), Moraceae (e.g., *Ficus* sp.) Elaeocarpaceae (e.g., *Elaeocarpus grandis*), Euphorbiaceae (e.g., *Aleutites mollucana*, *Macaranga* sp.), Myrtaceae (e.g., *Austromyrtus* sp., *Eugenia cormiflora*), and Rubiaceae (e.g., *Flindersia bray-
The vegetation around the lake margin is made of conspicuous zones of aquatic plant communities governed by water depth and seasonal fluctuations in water level (Kershaw, 1978). Rainforest lianas (e.g., Parsonia sp.) intertwine with tall swamp grass Phragmites sp. around the shallow lake edge. Hibiscus sp. and Ludwigia sp. become more common outside the influence of canopy shade and liana growth in the deeper (less than 1 m water depth) swamp margin. A zone of rooted emergent aquatics and floating vegetation mats is characterized by Cyclosorus gongylodes and Oenanthe sp., with Blechnum sp. and Elaeocharis equiseteum becoming common on less stable floating mats. As water depth increases to greater than 1 m, there is a transition from rooted emergent aquatics to floating aquatics, mainly Nymphaoides sp. which can occur as much as 30 m from the lake shore.

Methods

Fieldwork was conducted in the southern hemisphere winter of 1999. Parallel cores were taken from the center of the lake with a modified Livingstone corer with the mud–water interface section taken with a 1-m plastic piston corer and extruded at 1-cm intervals on site. Each core was described in detail and scanned by a magnetic susceptibility core-scanning loop at 1-cm intervals that identifies changes in the amount of ferrimagnetic minerals, which was used as an indication of changing erosional input to the lake. The cores were also sampled at 1-cm intervals for loss on ignition (at 550°C) to identify changes in the amount of combustible organic matter. Sampling for pollen analysis ranged from 2- to 8-cm intervals. Chronological control is provided by using $^{210}$Pb dating and AMS $^{14}$C analysis of bulk organic and pollen preparation samples extracted from the central portion of the sediment core (Table 1, calibrated years before present, where 0 cal yr B.P. = 1950 A.D, Stuiver et al., 1998).

Pollen analysis follows the standard KOH, HF, HCl and acetolysis method described by Bennett and Willis (2001). Samples from these lake deposits are generally organic-rich with high pollen concentrations calculated volumetrically with the addition of an exotic spike (Lycopodium clavatum). Pollen identification and nomenclature follows regional reference collections currently held at the School of Geography and Environmental Science, Monash University and the Department of Archaeology and Natural History at the Australian National University. Ecological information on the taxa represented in the pollen diagrams can be found in Kershaw (1970, 1971, 1975, 1983). Additional taxa identified in this analysis include Melaleuca comp. (Myrtaceae; a wet sclerophyll woodland tree in poorly drained soils), and Colocasia (Araceae, herb of poorly drained soils). Pollen counts are expressed as percentages of the total pollen sum (excluding pollen of aquatic vascular plants and spores of ferns and fern allies), which reaches a minimum of 300 in all samples.

Microscopic charcoal particle accumulation rates were calculated as concentrations of particles 10–125 μm encountered during pollen counting compared to exotic Lycopodium spike divided by the sediment accumulation rate. Macroscopic charcoal particle accumulation rates were calculated as concentrations of particles >125 μm determined at contiguous 1-cm intervals by treating 4 cm$^3$ sediment with KOH, mild bleach (6% Potassium Hypochlorite) overnight, sieved through a 125-μm sieve and counting total particles encountered under a low-powered (~10×) stereomicroscope. This provides basic data on the abundance of charcoal of different size fractions, the finer of which is most likely to be derived from long distance fires and the coarser fraction is likely to be derived from more local fire events.

Numerical zonation, rarefaction and Principle Components Analysis (PCA) were performed with only major taxa whose pollen or spore values exceeded 5% at least once. Numerical zonation employed optimal splitting by sum-of-squares analysis to partition the stratigraphically constrained fossil pollen assemblage data into significantly different pollen zones (after Bennett, 1996). Rarefaction analysis provides an estimate of the diversity of pollen types or palynological richness of each sample (Birks and Line, 1992). PCA is used to reduce the pollen and spore data to a two-dimensional plot and the resulting data set is displayed as a plot for samples and taxa (Birks and Gordon, 1985). All numerical analyses have been implemented within psimpoll, a program for plotting pollen data, developed by Bennett (1994).

Results and discussion

Lithology, sediment analysis and chronology

A total of 840 cm of lake muds and clays were recovered from the centre of the northern basin of Lake Euramoo from 1600 to 2440 cm bws (below water surface). The basal core encountered solid bedrock at a depth of 2440 cm bws. Overlying the bedrock are sediments composed of grey-green massive silty clays to 2365 cm bws that are characterized by low LOI values and peak magnetic susceptibility values (Fig. 2). Between 2365 to 2265 cm bws, the sediments are black lake muds with occasional bands (<1 cm thick) of light brown clayey muds decreasing in frequency up-core. Magnetic susceptibility values show a decreasing trend to minimum values at around 2320 cm bws. The LOI values increase up core with a sharp peak (60% organics) from 2320 to 2290 cm bws, followed by a reversal to lower LOI (30% organics) between 2290 to 2265 cm bws. Above 2265 cm bws to the mud water interface at 1600 cm bws, the sediments are uniformly dark brown lake muds with LOI values around 80–90%. A zone of coarse detritus and wood is encountered at 2000 to
1940 cm bws and is considered to be debris from a fallen tree or floating root mat and is excluded from the analysis.

Core chronology is based on a total of 22 AMS 14C dates on bulk organic detritus and pollen preparation samples (Table 1, derived from 5-mm-thick sample extractions). Fourteen sediment samples from the upper 46 cm of the core were dried overnight at 75°C, finely ground and analysed for 210Pb by ANSTO (Lucas Heights, Sydney). Sedimentation rates for the top 46 cm were derived from the analysis of 210Pb activity using the constant initial concentration (CIC) model (Appleby and Oldfield, 1983) and produced a basal 210Pb age of A.D 1880 at 1646 cm bws. The final age-depth model adopted for this study (Fig. 2) is derived by linear interpolation between a mud–water inter-

### Table 1

<table>
<thead>
<tr>
<th>ANSTO code</th>
<th>Sample Type and ID (cm below water level)</th>
<th>δ13C per mil</th>
<th>14C yr B.P.</th>
<th>1σ error</th>
<th>Calibrated age, cal yr B.P. (CALIB v4.4, 2σ error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OZE682</td>
<td>EU 1695–1696</td>
<td>−27.9</td>
<td>570</td>
<td>50</td>
<td>490–570 (80%)</td>
</tr>
<tr>
<td>OZE683</td>
<td>EU 1790–1790</td>
<td>−30.1</td>
<td>1320</td>
<td>40</td>
<td>1080–1110 (5%)</td>
</tr>
<tr>
<td>OZE684</td>
<td>EU 1857–1858</td>
<td>−31.8</td>
<td>2410</td>
<td>40</td>
<td>1170–1290 (86%)</td>
</tr>
<tr>
<td>OZE685</td>
<td>EU 1925–1926</td>
<td>−33.5</td>
<td>3510</td>
<td>40</td>
<td>2320–2490 (85%)</td>
</tr>
<tr>
<td>OZE686</td>
<td>EU 2040–2041</td>
<td>−31.7</td>
<td>4090</td>
<td>40</td>
<td>2630–2710 (15%)</td>
</tr>
<tr>
<td>OZE687</td>
<td>EU 2157–2158</td>
<td>−33.9</td>
<td>6210</td>
<td>50</td>
<td>3630–3840 (100%)</td>
</tr>
<tr>
<td>OZH310</td>
<td>EU 2201–2202</td>
<td>−31.1</td>
<td>5690</td>
<td>50</td>
<td>4420–4630 (92%)</td>
</tr>
<tr>
<td>OZH311</td>
<td>*EU 2219–2220</td>
<td>−31.7</td>
<td>7860</td>
<td>60</td>
<td>4760–4800 (8%)</td>
</tr>
<tr>
<td>OZH312</td>
<td>EU 2246–2247</td>
<td>−21.3</td>
<td>9400</td>
<td>80</td>
<td>6900–7210 (99%)</td>
</tr>
<tr>
<td>OZH313</td>
<td>EU 2255–2256</td>
<td>−25.5</td>
<td>9530</td>
<td>60</td>
<td>7220–7230 (1%)</td>
</tr>
<tr>
<td>OZEH688</td>
<td>EU 2263–2264</td>
<td>−28.5</td>
<td>9640</td>
<td>60</td>
<td>6640–6580 (9%)</td>
</tr>
<tr>
<td>OZH314</td>
<td>*EU 2270–2271</td>
<td>−23.2</td>
<td>9800</td>
<td>90</td>
<td>6570–6480 (86%)</td>
</tr>
<tr>
<td>OZH315</td>
<td>*EU 2275–2276</td>
<td>−29.1</td>
<td>10,130</td>
<td>60</td>
<td>8980–8910 (11%)</td>
</tr>
<tr>
<td>OZH316</td>
<td>Eu 2282–2283</td>
<td>−27.2</td>
<td>10,640</td>
<td>60</td>
<td>8900–8880 (4%)</td>
</tr>
<tr>
<td>OZEH388</td>
<td>EU 2292–2293</td>
<td>−24.0</td>
<td>11,100</td>
<td>60</td>
<td>8870–8830 (7%)</td>
</tr>
<tr>
<td>OZH317</td>
<td>*EU 2303–2304</td>
<td>−26.6</td>
<td>9110</td>
<td>60</td>
<td>11,360–11,060 (81%)</td>
</tr>
<tr>
<td>OZH318</td>
<td>EU 2315–2316</td>
<td>24.6</td>
<td>11,230</td>
<td>60</td>
<td>10,950–10,840 (9%)</td>
</tr>
<tr>
<td>OZE689</td>
<td>EU 2341–2342</td>
<td>−26.4</td>
<td>12,600</td>
<td>70</td>
<td>10,830–10,760 (3%)</td>
</tr>
<tr>
<td>OZH319</td>
<td>EU 2361–2362</td>
<td>−25.0</td>
<td>15,820</td>
<td>120</td>
<td>12,280–12,220 (3%)</td>
</tr>
<tr>
<td>OZH320</td>
<td>EU 2389–2390</td>
<td>−24.8</td>
<td>11,310</td>
<td>70</td>
<td>12,130–11,540 (83%)</td>
</tr>
<tr>
<td>OZH321</td>
<td>EU 2413–2414</td>
<td>−18.6</td>
<td>18,960</td>
<td>160</td>
<td>13,310–13,340 (1%)</td>
</tr>
<tr>
<td>OZE690</td>
<td>EU 2430–2435</td>
<td>−24.1</td>
<td>19,130</td>
<td>90</td>
<td>22,940–22,170 (100%)</td>
</tr>
</tbody>
</table>

All samples are derived from bulk organic detritus with the exception of 4 pollen preparation samples*. Calibration results from CALIB v4.4 (Stuiver and Reimer, 1993). The midpoint of calendar yr range marked in bold are used in age-depth model calculations (3 samples excluded from the age-depth model are not in bold).
face of A.D 1999, the first appearance of exotic pollen types taxa (Lantana, Mimosa, Pinus and Plantago, details in Haberle et al. in prep), the $^{210}$Pb profile, and the $^{14}$C age determinations. Three AMS $^{14}$C dates were excluded from the age-depth profile on the basis of poorest fit with the linear interpolation and may be the result of down-core contamination with younger carbon.

Pollen and charcoal record

The pollen record for Lake Euramoo is presented in Figures 3a–d and is divided into five zones that are described below. A summary interpretation of each zone is presented in Table 2.

**Lake Euramoo 23,000–16,800 cal yr B.P.**

(Zone Eu-A1, 2432–2340 cm bws)

Grasses and the sclerophyll woodland taxa, mainly Casuarina, Myrtaceae (dominated by Melaleuca comp.) and to a lesser extent Callitris dominate the diagram forming >95% of the pollen sum. Melaleuca comp. and the grasses alternate peak values with Casuarina. There is no significant presence of rainforest taxa and the palynological richness reaches a minimum in this zone. Locally, the presence of Cyperaceae, increasing sharply towards the top of the zone, and aquatic taxa such as Sparganium, Botryococcus and Pediastrum suggest that a swampy margin developed around a small open water body. The Cyperaceous swamp expanded markedly after about 18,000 cal yr B.P. and included a greater presence of Lycopodiaceae, Sparganium and the aquatic fern Selaginella. Fires appear to be infrequent throughout this zone.

**Lake Euramoo 16,800–8700 cal yr B.P.**

(Zone Eu-A2, 2340–2220 cm bws)

High values for sclerophyll taxa are maintained though there is an increase in the importance of Myrtaceous taxa, including the wet sclerophyll Eucalyptus types. Callitris increases to its highest values in the record. Grasses and Compositae decrease with minor increases recorded in Alternanthera and Liliaceae between 16,000 and 10,600 cal yr B.P. The first appearance of 36 rainforest taxa, dominated by Urticaceae/Moraceae, is recorded in this zone which is
reflected in a doubling of the palynological richness by 15,500 cal yr B.P. The rainforest gymnosperms Agathis and Podocarpus appear for the first time by 15,500 cal yr B.P. but then are absent between 12,600 and 9600 cal yr B.P. Rainforest taxa as a whole make up between 10% and 20% of the pollen sum between 16,800 and 11,500 cal yr B.P., but then show a reversal to dry sclerophyll taxa dominance (mainly Casuarina) between 11,500 and 9600 cal yr B.P. Regional pollen dispersal from the lowland mangrove swamps is also incorporated into the Lake Euramoo sediments and may reflect increased convection or more extensive mangrove forests along the coastal margins as sea level stabilizes during the early Holocene (Clark and Guppy, 1988). The Cyperaceae swamp dominates the lake margin until 15,500 cal yr B.P. but then becomes a less significant feature of the lake edge vegetation after this time. Ferns also begin to become important in this zone. Fire is much more prominent in the landscape after 16,800 cal yr B.P. The fire record is dominated by fine charcoal particles derived from regional as well as local (probably grass dominated) fires. By around 11,500 cal yr B.P. the coarser charcoal fraction begins to increase perhaps in response to reduced grassy understorey and the development of a more dominant woody understorey.

Lake Euramoo 8700–5000 cal yr B.P.
(Zone Eu-A3, 2220–2050 cm bws)

At 8700 cal yr B.P. there is a rapid shift from sclerophyll to rainforest dominance in the pollen spectrum. Casuarina, Myrtaceae, Callitris and the grass percentages all fall to low values, reaching a minimum by 7300 cal yr B.P., as the total rainforest taxa contribution to the pollen sum rise sharply to around 80–90%. Urticaceae/Moraceae, Mallotus/Macaranga, Trema, Cunoniaceae, Elaeocarpus and ferns (mainly Filicales-psilate type) all show sustained increase in percentages through this zone. Podocarpus shows an initial increase and then declines by around 7300 cal yr B.P. A further 19 rainforest taxa make their first appearance in this zone, though the palynological richness reaches a high level at the base of this zone that is maintained for the rest of the record, reflecting a balance of taxa losses as well as gains during this transition. The swamp herbs Colocasia, Haloragis and an undetermined Umbelliferae are incorporated into the local cyperaceous swamp. The charcoal record is dominated by the coarse charcoal fraction through to about 7300 cal yr B.P. possibly reflecting continued burning of the rainforest-sclerophyll woodland margin during the early Holocene. Total charcoal reaches a minimum between about

Figure 3. Lake Euramoo pollen diagram. (a) Summary pollen diagram with rarefaction analysis and principal components analysis results, and charcoal accumulation rates (2 size fractions: 10–125 μm and >125 μm). (b) % diagram of herbaceous, sclerophyll woodland and rainforest taxa included within the total pollen sum (dot =<1%). (c) % diagram of minor rainforest taxa included within the total pollen sum (dot =<1%). (d) % diagram of swamp herbs, aquatics, ferns and other palynomorphs excluded from the total pollen sum.
Figure 3 (continued).
Figure 3 (continued).
7300 and 6300 cal yr B.P. at the same time as rainforest taxa attain maximum percentage representation of close to 100% of the pollen sum. The coarse charcoal fraction then makes a sustained increase after 6300 cal yr B.P. and is accompanied by rises in *Trema* a pioneer rainforest taxon.

**Lake Euramoo 5000–70 cal yr B.P.**

(Zone Eu-A4, 2050–1646 cm bws)

This zone is separated from the previous zone by a sustained rise in *Elaeocarpus*, closely associated with slight rises in *Agathis* and *Mallotus/Macaranga*. *Cunoniaceae* generally decrease while *Urticaceae/Moraceae*, *Cunoniaceae* and *Podocarpus* maintain constant percentage values in this zone. Fine and coarse charcoal particles are present throughout with a series of peaks in coarse charcoal deposition recorded from 4000 cal yr B.P. onwards and a rise in accumulation rate between 2700 and 1200 cal yr B.P. At around 1200 cal yr B.P., a further rise in *Elaeocarpus* is accompanied by slight increases in sclerophyll taxa and a decrease in *Agathis*, *Mallotus/Macaranga* and *Trema*. A decrease in *Cyperaceae* and an increase in the aquatics, *Sparganium*, *Nymphoides* and *Botryococcus*, suggest a return to more open water conditions at this time. The appearance of the swamp fern *Thelypteridaceae* (most likely *Cyclosorus gongylodes*), a weedy fern

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**Table 2**

Interpretation of Lake Euramoo pollen zones and equivalent zones represented in the Lake Euramoo edge core (Kershaw, 1970)

<table>
<thead>
<tr>
<th>Pollen zone</th>
<th>Age cal yr B.P.</th>
<th>Interpretation of pollen spectra</th>
<th>Equivalent pollen zone Kershaw 1970</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eu-A1</td>
<td>23,000–16,800</td>
<td>Dry sclerophyll woodland dominated by fire-sensitive <em>Casuarina</em> with a grassy understorey. A sedge swamp surrounds a small permanent open water body with local Melaleuca swamp around the lake edge margins.</td>
<td>Not evident</td>
</tr>
<tr>
<td>Eu-A2</td>
<td>16,800–8700</td>
<td>Wet sclerophyll woodland with marginal rainforest in protected pockets or forming rainforest mosaics with drier woodland formations. Fire becoming increasingly prevalent with increase in fire-promoting woody flora.</td>
<td>Zone 1</td>
</tr>
<tr>
<td>Eu-A3</td>
<td>8700–5000</td>
<td>Lower montane rainforest with relative dominance by <em>Cunoniaceae</em> and <em>Urticaceae/Moraceae</em> with fire virtually absent.</td>
<td>Zone 2, 3</td>
</tr>
<tr>
<td>Eu-A4</td>
<td>5000–70</td>
<td>Sub-montane rainforest dominated by <em>Elaeocarpaceae</em>, <em>Agathis</em> and <em>Trema</em> with fire increasingly prevalent.</td>
<td>Zone 4, 5</td>
</tr>
<tr>
<td>Eu-A5</td>
<td>AD 1880–1999</td>
<td>Degraded sub-montane rainforest with increasing influence of invasive species and fire.</td>
<td>Surface samples only</td>
</tr>
</tbody>
</table>

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**Figure 4. Principle components analysis of the Lake Euramoo pollen data from the Kershaw (1970) lake edge core and the lake centre core taken in 1999 from this paper.** The analysis included only taxa with >5% representation common to both records (Rut. = Rutaceae/Araliaceae, Cunon. = Cunoniaceae) with eigenvalue axis 1 = 63% and axis 2 = 8%. Sample symbols distinguish pollen zones from each site and the direction of change is indicated by grey solid (lake centre core) and grey dashed (lake edge core) arrow.
recorded in disturbed swampland across the Pacific (Powell, 1982; Mueller-Dombois and Fosberg, 1998) around 10,000 cal yr B.P. suggests the floating mat habitat may have expanded as well in the last millennia.

Lake Euramoo A.D 1880–1999
(Zone Eu-A5, 1646—1600 cm bws)

This zone is separated from the preceding zone by the appearance of exotic species Lantana, Mimosa, Plantago, Pinus, Solanaceae and Rumex, introduced during the period of European settlement, beginning in the early A.D 1880s. Sclerophyll taxa maintain constantly low values whereas several rainforest taxa show marked declines including Urticaceae/Moraceae, Elaeocarpus and Agathis, most likely as a result of removal of the taxa due to selective logging during the 19th Century (Birtles, 1988). Increases are recorded in Rutaceae/Araliaceae, Trema, Cumoniacae, Sloanea and Eugenia. Charcoal particle accumulation rates return to high values comparable with those recorded in the early Holocene, though there is little apparent impact on the total rainforest taxa percentage of the pollen sum.

Comparison between lake edge and lake centre pollen record

The PCA ordination (Fig. 4) incorporates two fossil pollen datasets from Lake Euramoo. The diagram compares the extended Lake Euramoo pollen record from the lake centre (23,000 cal yr B.P. to present) with the lake edge core collected by Kershaw (1970) that spanned the Holocene from 23,000 cal yr B.P. to present) with the lake edge core. Several rainforest taxa show marked declines including Urticaceae/Moraceae, Elaeocarpus and Agathis, most likely as a result of removal of the taxa due to selective logging during the 19th Century (Birtles, 1988). Increases are recorded in Rutaceae/Araliaceae, Trema, Cumoniacae, Sloanea and Eugenia. Charcoal particle accumulation rates return to high values comparable with those recorded in the early Holocene, though there is little apparent impact on the total rainforest taxa percentage of the pollen sum.

Discussion
An extended sclerophyll woodland phase at Lake Euramoo

The new pollen record from Lake Euramoo extends the old record by around 12,000 cal yr B.P. to include the Last Glacial Maximum. Kershaw (1970: 797) originally hypothesized that the persistence of sclerophyll woodland in the early Holocene part of the record was a consequence of recent (early Holocene) volcanic activity at the site and that the earliest vegetation then evident from the pollen record represented pioneer vegetation establishing on immature soils. The new core from the lake centre clearly refutes the possibility of early Holocene volcanic activity from the Euramoo crater, placing a minimum age for crater formation of >23,000 cal yr B.P. There is no indication in the pollen record that vegetation went through successional phases of establishment on maturing basalt soils around the site after 23,000 cal yr B.P. As sediments accumulated over basalt bedrock the regional vegetation remains dominated by fire-sensitive Casuarina with a grassy understorey, though the alternating peaks in Melaleuca comp. and the grasses with Casuarina, possibly reflect millennial-scale shifts in regional soil moisture or salinity during this period (Crowley, 1994). Swamp vegetation persists locally throughout this early period.

Pollen and sediment evidence from Lynch’s Crater (Turney et al., 2004; Kershaw, 1994), sea surface temperature reconstructions from the Coral Sea (Barrows and Juggins, in press; Anderson et al., 1989) and fluvial geomorphology from NE Queensland (Thomas et al., 2001) all point to conditions on the Atherton Tablelands at this time being much drier (up to 50% reduced precipitation) and cooler (2°–5°C) than today. The low levels of charcoal preserved in the Lake Euramoo sediments suggests that the maintenance of the sclerophyll woodland community around Lake Euramoo was most strongly associated with the climatic controls of low precipitation rather than a high burning frequency. Similar conditions are reflected in the Lynch’s Crater (zone L2 lower section) and Strenekoff’s Crater (zone S2 lower sample) record, where samples closest to the LGM in these records show relatively high Casuarina—low Eucalyptus pollen percentages accompanied by low charcoal densities (Kershaw, 1994). This is at odds with reconstructions of biomass burning further to the north in the equatorial highlands of New Guinea where cumulative charcoal records from wet montane forest/grassland settings suggest a high rate of charcoal production between 20,000 and 10,000 cal yr B.P. The New Guinea records have been interpreted as resulting from greater variability in rainfall patterns, during the late glacial period, enhancing the potential for frequent fires (Haberle et al., 2001). The combined effect of relatively lower annual precipitation and the lower biomass of sclerophyll woodland in the Atherton Tablelands may have been sufficient to reduce charcoal deposition during the late glacial period in Lake Euramoo and it is not until increased woodiness, in response to increased precipitation of the late glacial transition phase, that charcoal production also increased.

Eucalyptus
Four phases of rainforest development

The transition from sclerophyll woodland to rainforest as recorded at Lake Euramoo can be considered to have taken 9500 yr, with the initial indication that rainforest was reinvading the Atherton Tablelands from glacial refugia beginning at 16,800 cal yr B.P. and being completed by 7300 cal yr B.P. The development of rainforest appears to occur in four phases.

The first phase begins at 16,800 cal yr B.P., when a limited suite of rainforest angiosperm and gymnosperm taxa and wet sclerophyll taxa first appear near the site, possibly as insipient rainforest patches forming mosaics with wet sclerophyll woodland. This is almost 4000 yr earlier than similar changes noted in other Atherton Tablelands records (Walker and Chen, 1987; Hiscock and Kershaw, 1992) and may reflect closer proximity of Lake Euramoo to glacial rainforest refugia, more favorable geology (basalts) for early establishment of rainforest, or the wet swampy lake margins providing restricted refugia for rainforest taxa as precipitation and temperature increased during the late glacial transition. Increased organic accumulation and biomass burning are associated with this phase, which supports the suggestion that a rise in woody plant biomass may have been a factor in rising charcoal particle accumulation rates in the sediments.

The second phase spans the period from 12,600 to 9600 cal yr B.P. and is marked by the disappearance of a number of rainforest taxa from the record, including Agathis and Podocarpus, and a return to peak representation of Casuarina in place of wet sclerophyll woodland. This may represent a reversal towards drier climatic conditions, however, rainforest taxa continue to make initial appearances in the record suggesting that taxa disappearances may represent shifts in canopy dominance through competitive advantage rather than a reversal in climatic conditions necessarily restricting rainforest advancement into the area.

The third phase occurs between 9600 and 8700 cal yr B.P. when the maximum rate of increase in rainfall, led by taxa typical of lower montane rainforest, is recorded at Lake Euramoo. This is most likely to represent the local establishment of closed canopy rainforest under the influence of increasing precipitation at the site. This occurs within a 900-yr period and is comparable to the period of time recorded at other sites on the Atherton Tablelands where the transition from sclerophyll woodland to rainforest dominance has been estimated to have taken between about 400 and 1000 yr on the Atherton Tablelands (Hiscock and Kershaw, 1992).

The final phase of rainforest development involves the gradual exclusion of sclerophyll woodland prior to the peak development of lower montane rainforest at 7300 cal yr B.P. Local dominance of rainforest was achieved despite the persistent recurrence of fires that appear to have maintained local patches of sclerophyll woodland and may have retarded the encroachment of rainforest onto the site.

The non-synchronous and non-linear nature of the sclerophyll to rainforest transition recorded at five sites on the Tablelands points to local as well as regional environmental variables influencing the development of rainforest through time. The apparent contradiction that the most intensive fire period occurs during the phase of most rapid increase in fire sensitive rainforest suggests that fire may have become decoupled from the natural climate regime and was at least partially controlled by aboriginal fire practices. The motivation for maintaining open sclerophyll woodlands in an ever encroaching rainforest landscape may have stemmed from the need to maintain open habitats that were so prevalent during the late glacial period for hunting, mobility and to exploit woodland plant diversity for food procurement (Hill and Baird, 2003; Horsfall, 1987).

Rainforest dynamics during the mid–late Holocene

Around 7300 to 6300 cal yr B.P. rainforest achieved its maximum extent across the Atherton Tablelands under conditions of higher than present wet season temperatures and higher dry season precipitation (Kershaw and Nix, 1988). This effectively would have reduced annual climate seasonality resulting in low potential for dry-season burning of sclerophyll woodland and limited moisture loss from rainforest habitats reduced its vulnerability to fire. Reduced seasonality may have been partially driven by orbital forcing according to the Milankovitch theory, which predicts a minimum in Southern Hemisphere summer insolation from ~12,000 to 9000 cal yr B.P., with an increase toward the present (Berger and Loutre, 1991). In the Lake Euramoo record, the maximum rainforest extent of rainforest occurs at least 2000 yr after the insolation minimum. One explanation for this apparent lag in vegetation response to Milankovich forcing lies in the strong influence of southeast trade winds on precipitation in the Atherton Tablelands today. In the past precipitation at Lake Euramoo would have been influenced by the proximity of the coastline. Rising sea levels during the late-glacial transition flooded the continental shelf adjacent to the Atherton Tablelands as well as flooding the Torres Strait, between northern Australia and New Guinea, with current conditions only being attained by around 8000 to 7000 cal yr B.P. (Woodroffe et al., 2000). The combined impact of reduced continentality, increased moisture convection over the Torres Strait leading to greater southern penetration of the ITCZ during the southern summer, may have been the primary driver increasing delivery of rainfall to Lake Euramoo after 8700 cal yr B.P. and during the mid Holocene period.

The evidence for a sustained onset of increased burning after 6300 cal yr B.P. and the appearance for major infrequent (every 250–1000 yr) peaks of charcoal after 4000 cal yr B.P. is accompanied by evidence for greater disturbance of the rainforest, suggesting that the charcoal source was not restricted to patches of sclerophyll woodland (currently within 1 km from the site) but may indicate fires occurring within the rainforest resulting in an opening up of the canopy. Similar fire frequencies are suggested for the Lake Barrine catchment area during the period of rainforest encroachment (Chen, 1988) and this may represent a general fire return time for rainforests in the region. Increased rainforest disturbance may have been
driven by overall drier conditions or increased rainfall seasonality (Kershaw and Nix, 1988). In addition, the potential influence of intensified El Niño activity after ~5000 cal yr B.P. that has been suggested from eastern (Sandweiss et al., 1996; Rodbell et al., 1999) and western Pacific (Haberle et al., 2001; Hayne and Chappell, 2001) proxy records and would likely have a significant impact on rainforest dynamics in the Atherton Tablelands region. The shift in the Lake Euramoo pollen assemblage towards greater representation of short-lived taxa such as *Mallotus/Macaranga*, after 5000 cal yr B.P. may well be indicative of an overall increase in ecosystem turnover rates under the influence of more frequent El Niño-related disturbance events. Alternatively, or at least overlaying these climatic factors there may have been a greater intensity of occupation and resource management by aboriginal populations after about 4000 cal yr B.P. facilitated through a broadening of the range of foodstuffs consumed and the commencement of toxic plant exploitation (Horsfall, 1987; Haberle and David, 2004). Destruction of the swamp forest on Lynch’s Crater at about 5000 cal yr B.P. has also been linked to aboriginal exploitation and intensified use of fire at this time (Hiscock and Kershaw, 1992). The slight rise in total charcoal accumulation rate and increased frequency of major charcoal peaks between 2500 and 1500 cal yr B.P. may also point to a period of intensified burning activity near Lake Euramoo. The relative contribution of climate change and human activity to these changes remains a complex question that ultimately may not be resolved if we assume an interdependence of human response to environmental conditions (Haberle and Chestow-Lusty, 2000; Haberle and David, 2004).

The pollen record of the last few hundred years at Lake Euramoo, missing in the original lake edge core (Kershaw, 1970), details the first appearances of exotic pollen (*Lantana, Mimosa* and *Pinus/Plantago*) and the dramatic rise in charcoal accumulation rate in the lake sediments provide a clear stratigraphic marker for European occupation and land use in the region. The fine-resolution record of the upper 100 cm shows that the present composition of rainforest in this region has been significantly altered over the last 120 yr, most notably evident through the reduction of key taxa in the pollen record, including *Agathis* and *Podocarpus* (Figs. 3b and 4), both exploited for the timber industry during the early 19th Century (Birtles, 1988). The most significant changes are recorded at the onset of European occupation between about A.D 1880 and 1920, through clearance and burning activities. These changes were rapid and their impact appears to have persisted through the last century with no sign of recovery to a pre-European assemblage despite nearly 50 yr of fire management and rainforest conservation.

**Conclusions**

The extended pollen record from Lake Euramoo represents a complete record of vegetation change from the LGM to present incorporating the transition from sclerophyll woodlands to rainforest. Detailed analysis of the transition including a high-resolution contiguous record of charcoal particle accumulation rates suggests that the progression of rainforest expansion at the beginning of the Holocene was neither synchronous with climate change nor unidirectional implying a much more complex model for rainforest development incorporating external (regional climatic) as well as local (topographic, anthropogenic) factors. The process of rainforest expansion takes about 9500 yr, beginning around 16,800 cal yr B.P. and proceeding through a non-linear four-phase development until maximum rainforest extent is achieved by 7300 cal yr B.P. Fire appears to play a major role in the development of early rainforest cover, both through general retardation of rainforest expansion and by providing competitive advantage to fire-tolerant and pioneer species. Tropical biomass burning appears to be at least partly controlled by orbital forcing (precession), though biomass change and human activity are also significant factors. Shifts towards competitive dominance of taxa adapted to drought/fire (e.g., *Agathis, Mallotus/Macaranga, Podocarpus* and *Trema*) are most prevalent in the Lake Euramoo catchment after 5000 cal yr B.P., which may be a response to the intensification of El Nino-related climate variability and/or increased human activity within north Queensland tropical rainforest.

This new record provides the opportunity to explore the relationship between fire, drought and rainforest dynamics in a significant World Heritage rainforest region. That vegetation changes and fire episodes are not always synchronous with regional climate change through time supports the notion that climate thresholds and ecological or vegetation thresholds are not necessarily the same, nor once they are crossed are they necessarily reversible (Maslin, 2004).

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**References**


