The impact of European occupation on terrestrial and aquatic ecosystem dynamics in an Australian tropical rain forest

SIMON G. HABERLE, JOHN TIBBY*, SOPHIA DIMITRIADIS† and HENK HEIJNIS‡

Resource Management in Asia-Pacific Program, Research School of Pacific and Asian Studies, Australian National University, Canberra, ACT 0200, Australia, *Geographical and Environmental Studies, University of Adelaide, Adelaide, SA 5005, Australia, †School of Botany and Zoology, The Australian National University, Canberra, ACT 0200, Australia, and ‡Australian Nuclear Science and Technology Organization, PMB 1, Menai, NSW 2234, Australia

Summary

1 The long-term impact of changes in land use, fire and climate on species diversity in Australia are only just beginning to be understood. We combined fine-resolution palaeoecological proxies for terrestrial and aquatic ecosystems to investigate the responses of a tropical rain forest catchment over the last 700 years.

2 Sediment cores were sampled at 1-cm intervals to a depth of 100 cm from Lake Euramoo on the Atherton Tableland of north-east Queensland, dated and analysed for pollen, charcoal, diatom, chironomid and inorganic content.

3 The pollen and charcoal record shows a rapid loss of forest diversity (particularly the long-lived taxa Agathis and Podocarpus) and increased burning coinciding with the arrival of European settlers. The aquatic environment is also subject to rapid changes at this time, with a possible increase in pH and subsequent shifts in local algal and insect communities. This event was outside the historic range of variability in both rain forest and aquatic communities.

4 The present mosaic of vegetation types is a complex function of environmental changes operating across a range of spatial and temporal scales: millennial climate change, short-term climatic variations associated with El Niño events and, most significantly, a shift from indigenous to ‘European’ land-use practices, including clearance and burning activities associated with the timber and farming industry between about AD 1880 and 1920.

5 The establishment of a World Heritage reserve around the lake catchment and the suppression of fire over the last 50 years have not yet restored the terrestrial or aquatic ecosystem to its pre-European state and are unlikely to, given the current predictions of future climate change. This supports the notion that ecological and climate thresholds are not necessarily the same, and that the effects of crossing them are not necessarily reversible. Retrospective studies of the historic range of variability within small catchments can provide an understanding of the limits of natural and human-induced variability that can inform management decisions and resource planning.

Key-words: alternate states, Atherton Tableland, Australia, charcoal, chironomids, diatoms, disturbance, historic range of variability, pollen, tropical rain forest

Introduction

Australia, with its diversity of ecosystems, late colonial settlement and absence of previous agricultural activity, offers advantages over other developed nations for studying the effects of industrial agriculture on the physical environment. Description of the ecological changes during the period of European settlement of Australia has generally fallen to those deriving their primary data from historical documents or ‘long-term’ ecological data (Kirkpatrick 1999; Bowman et al. 2001;
These studies show that Australian ecosystems are highly dynamic and have undergone significant change through most of the last century due to land-use and climate change. However, there is a rapid loss of quality and quantity of primary data with increasing antiquity and, with this, a diminishing capacity to understand the rate, magnitude and root causes of ecological change during the early stages of settlement. The need to understand these deeper temporal dynamics of ecosystem change, which can occur at decadal to millennial scales, is crucial if realistic models of ecosystem response to future change are to be developed (Whittaker et al. 2005).

Although vegetation dynamics on millennial timescales are well understood in the Australian wet tropical rain forest, our understanding of vegetation dynamics during the last thousand years is limited to insights from fragmentary pollen records from the Atherton Tableland (Kershaw 1970, 1971, 1975, 1983). The original sediment sequences from Lake Euramoo (Kershaw 1970), Quincan Crater (Kershaw 1971), Bromfield Swamp (Kershaw 1975) and Lynch’s Crater (Kershaw 1983) are discontinuous or disturbed near the surface, with the youngest age being around 800 yr for the upper samples. The contrast between recent (European period) and pre-European (> 800 yr) depends on inclusion of pollen assemblages from surface samples (floating root mats) into these pollen records. In general, this comparison shows that an increase in disturbance-related pollen taxa, such as Cyclosorus and Trema, and a loss of some long-lived forest pollen taxa, including Elaeocarpus and Agathis, occurred around the time of European settlement. A 1000-year laminated sediment record from Lake Barrine shows little identifiable change in vegetation characteristics over this time period beyond the appearance of pollen of introduced species of Solanum (Walker & Owen 1999; Walker et al. 2000), although the large size (c. 1 km²) and rain forest covered catchment of the lake may have limited its sensitivity to changes in land use over this time.

European settlement of the rain forest ecosystems of north-eastern Australia was a relatively late event and did not occur until the end of the 19th century because of the remoteness from the then administrative centre of Port Jackson (Sydney) and a perception of the region as impenetrable and economically barren (Birtles 1982). In addition, early encounters between European explorers and Aboriginal peoples created a perception of the indigenous population as dangerous, although resistance to encroachment appears to have been brief, possibly because disease led to rapidly diminished populations. Little is known about occupation of the rain forest prior to European settlement, although recent archaeological research indicates that Aboriginal peoples have had the technological capacity to subsist in these forests for at least 7500 years, and to occupy them intensively for the last 1800 years (Cosgrove 2005). Such people relied on several species of fruit trees (Beilschmiedia spp., Elaeocarpus spp. and Aleurites moluccana), as well as rootstocks of wild yam (Dioscorea spp.), and had mastered the complex processing required to obtain substantial quantities of protein and carbohydrates from highly toxic cycads (Cycas spp.) (Hill & Baird 2003). Fire was used to maintain open tracks and grassland pockets throughout the rain forest up until the arrival of Europeans in the 1880s (Birtles 1982; Hill et al. 1999).

Recent, and future, climate change may be a potentially more significant influence on the extent and survival of rain forest species and ecosystems (Williams et al. 2003). Bioclimatic models of rain forest habitats suggest that, with only 1 °C warming and 10% decrease in rainfall, the spatial extent of highland rain forest environments could decrease by 50%, posing a threat to the survival of several key vertebrate species (Hilbert et al. 2004). However, the widespread cessation of aboriginal burning practices in the 19th Century and increases in atmospheric CO₂ in the late 20th Century favour expansion of such habitat (Hopkins et al. 1996; Crowley & Garnett 2000; Russell-Smith et al. 2004). How these complex interactions between climate and land-use change will play out in the next century is critical for the long-term survival and management of this ecosystem.

We explore the potential of using high-resolution multiproxy palaeoecological data spanning the last 700 years to investigate the nature and direction of ecological change in the rain forest environment of the Atherton Tableland. We use fossil records of pollen, charcoal, invertebrates and aquatic algae to provide a window into past ecosystem change, concentrating on the period of transition marked by the arrival of European settlement in 1881, to address specific questions:

1. How did European land-use activity influence terrestrial and aquatic ecosystems and lead to the modern rain forest environment?
2. Did European land-use activity represent an unprecedented event that lay outside the historic range of variability?
3. How has climate change influenced terrestrial and aquatic ecosystems and what impact might it have on the future of the rain forest environment?

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, 17°10′S, 146°38′E) on the Tertiary uplifted highlands of the Atherton Tableland (Fig. 1) and within an area that contains Australia’s most significant expanse of tropical rain forest. 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 around 4.4 ha 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).
More than 60% of the estimated annual average rainfall of 1500 mm falls between January and March (Kershaw 1970), so that the winter is distinctly dry. The lake lies at the drier end of a steep, east to west rainfall gradient. The dominant source of precipitation is the south-east Trades, although occasional north-westerly monsoonal flows, and associated tropical cyclones, 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 & Reason 2002). During El Niño episodes, a northward movement of the ITCZ and a north-eastward 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 & Wigley 2000).

Mean daily maximum and minimum temperatures are around 25.9 °C and 14.4 °C, respectively, and frosts occur infrequently during the austral winter months at times of weak trade winds and low cloud cover.

The first European incursions over the escarpment and into the Atherton Tableland region were associated with timber taking (mainly of *Toona australis* 'Red Cedar' and *Agathis palmerstonii* 'Kauri'), beginning in 1881. Pastoral interests, timber and a series of gold rushes had lured colonists northwards in the 1870s and 1880s, increasing efforts to settle the rain forest region. Establishment of dairy farms to supply the goldfields towards the coast, as well as the developing upland settlements of Herberton and Atherton, exacerbated the rate of forest clearance. Aboriginal populations were dispersed and decimated during these early decades and soldier settlement schemes, from 1905 to 1915 and during the mid 20th century, increased land clearance and population pressure in the region (Birtles 1988). The designation of remnant patches of rain forest, such as Lake Barrine and Lake Eacham, as National Parks in the 1930s provided some protection from logging. While it is estimated that only around 14% of the rain forest had been cleared by 1985 (Winter et al. 1987), the selective extraction of economically valuable species had a far wider impact.

The terrestrial vegetation surrounding Lake Euramoo is a remnant of moist submontane rain forest surrounded by previously cleared land that, within the last 50 years, has either been planted with endemic Hoop Pine (*Araucaria cunninghamii*) and exotic conifers or has undergone secondary colonization towards re-establishing rain forest. Over 100 species of rain forest tree and shrub have been recorded within 100 m of Lake Euramoo (A. P. Kershaw personal communication). Typical moist submontane rain forest species found near Lake Euramoo include members of the Araliaceae (e.g. *Polyscias australiana*, *Scheflera actinophylla*), Araucariaceae (e.g. *Agathis robusta*), Moraceae (e.g. *Ficus* sp.), Elaeocarpaceae (e.g. *Elaeocarpus grandis*), Euphorbiaceae (e.g. *Aleurites moluccana*, *Macaranga* spp.), Myrtaceae (e.g. *Austromyrtus* spp., *Eugenia cormiflora*) and Rubiaceae (e.g. *Flindersia brayleyana*, *Euodia bonwickii*). The nearby (< 1 km) drier vegetation communities include tall open forest (sclerophyll woodland) dominated by *Casuarina* spp. and *Eucalyptus* spp. At higher altitude, cool lower montane rain forest is increasingly dominated by members of families such as the Cunoniaceae (e.g. *Calchuvia australiensis*, *Schizomeria whitei*), Podocarpaceae (e.g. *Podocarpus* spp., *Prumnopitys* spp.) and Rhamnaceae (e.g. *Alphitonia* spp.).

Weedy species, of which the shrub *Lantana camara* is the most common, frequently invade roadsides and disturbed areas. The native vegetation around the lake margin consists of conspicuous zones of aquatic plant communities governed by water depth and seasonal fluctuations in water level (Kershaw 1978). Rain forest lianas (e.g. *Parsonsia* spp.) intertwine with the tall swamp grass *Phragmites australis* around the shallow lake edge.
**Table 1** Lake Euramoo: radiocarbon dates and calibrated ages (cal year BP = years before 1950) determined using the Calib 4.0 software (Stuiver et al. 1998)

<table>
<thead>
<tr>
<th>Sample material</th>
<th>Depth from sediment surface (cm)</th>
<th>Laboratory code</th>
<th>Percentage modern carbon δ13C (%o)</th>
<th>Conventional 14C age (year BP)</th>
<th>Calibrated age range cal year BP (% prob. 1σ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic detritus</td>
<td>95–96</td>
<td>OZE682</td>
<td>92.90 0.54</td>
<td>590 40</td>
<td>642–592 (71.9%) 563–549 (28.1%)</td>
</tr>
<tr>
<td>Organic detritus</td>
<td>190–191</td>
<td>OZE683</td>
<td>84.36 0.36</td>
<td>1370 40</td>
<td>1303–1272 (100%)</td>
</tr>
</tbody>
</table>

**Table 2** Time markers used to construct the age-depth model for sedimentation and sedimentation accumulation rates at Lake Euramoo

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Age estimate (year AD)</th>
<th>Age estimate based upon</th>
<th>Sediment accumulation rate (cm year⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–1</td>
<td>1999</td>
<td>Assumed to represent present</td>
<td>0.32</td>
</tr>
<tr>
<td>12–13</td>
<td>c. 1960</td>
<td>Appearance of weed pollen: Pinus and Plantago</td>
<td>0.26</td>
</tr>
<tr>
<td>24–25</td>
<td>c. 1912</td>
<td>Appearance of weed pollen: Mimosa</td>
<td>0.48</td>
</tr>
<tr>
<td>40–41</td>
<td>c. 1880s</td>
<td>Appearance of weed pollen: Lantana</td>
<td>0.13</td>
</tr>
<tr>
<td>45–46</td>
<td>1850–1920</td>
<td>210Pb age determination</td>
<td>0.10</td>
</tr>
<tr>
<td>95–96</td>
<td>1340</td>
<td>Calibrated AMS 14C age determination</td>
<td>0.13</td>
</tr>
<tr>
<td>190–191</td>
<td>660</td>
<td>Calibrated AMS 14C age determination</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Hibiscus spp. and Ludwigia spp. become more common in the deeper (but still less than 1 m water depth) swamp margin (i.e. outside the influence of canopy shade and liana growth). A zone of rooted emergent aquatics and floating vegetation mats is characterized by Cyclosorus gongyloides and Oenanthe spp., with Blechnum spp. and Eleocharis spp. 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 Nymphoides spp., which can occur as much as 30 m from the lake shore.

**Methods**

Fieldwork was carried out in April–May 1999. The uppermost 100 cm of sediment was obtained, using a clear plastic piston corer, from the centre of the northern basin of Lake Euramoo, where the water depth measured 1600 cm. This method allows for undisturbed recovery of the mud–water interface. The two sections of core, which measured from 0 to 68 cm depth and 69 to 100 cm depth, were divided into contiguous 1-cm intervals on-site.

**SEDIMENTATION AND CHRONOLOGY**

Samples were analysed for loss-on-ignition (%LOI) by combusting dried sediment at 500 °C for 5 hours. Chronological control of the record was provided using a combination of 14C, 210Pb and first appearance of exotic pollen types (Tables 1 and 2). Conventional 14C dates were obtained on two bulk organic sediment samples at 95 cm and 190 cm depth (Table 1), the latter from a longer core (Haberle 2005). Fourteen sediment samples from the upper 25 cm of the core were dried overnight at 75 °C, finely ground, and analysed for 210Pb by ANSTO (Australian Nuclear Science and Technology Organisation, Sydney, Australia). Sedimentation rates were derived from the analysis of 210Pb activity using the constant initial concentration (CIC) model (Appleby & Oldfield 1983). Constant rate of supply (CRS) model calculations were not derived, because a full inventory of excess 210Pb could not be calculated as excess 210Pb was still present in the bottom sample.

**POLLEN, SPORES AND CHARCOAL**

The terrestrial and aquatic flora is represented by the pollen and spore assemblage preserved in the lake sediments. Pollen and spore analysis followed standard procedures (Bennett & Willis 2001). Pollen counts are expressed as percentages of the total pollen sum (excluding pollen of aquatic vascular plants and spores), which reaches a minimum of 200 in all samples. The timing of European settlement in the core was assessed from changes in pollen representing introduced weeds, including Lantana, Mimosa, Plantago, Pinus, Solanaceae and Rumex (based on Queensland Herbarium records). Concentrations of pollen, spores and microscopic charcoal (c. 10–125 µm) were calculated by relative abundance with respect to a known concentration of Lycopodium. Concentrations of larger particles of charcoal (> 125 µm) were determined as an indicator of fires occurring relatively close to the site (Clark & Royall 1995; Millsopha & Whitlock 1995).

**DIATOMS**

Diatoms are unicellular organisms characterized by their siliceous cell walls and are particularly sensitive to physical, chemical or biological changes in aquatic habitats (Battarbee et al. 2001). Samples for diatom analysis were taken at 2–4 cm intervals down the core.
from the same depth as the samples for pollen analysis (with the exception of 1 and 3 cm, which were not analysed for diatoms) and prepared using a modified version of the technique outlined in Renberg (1990). Diatoms were identified at 1000× magnification, using a Zeiss Axioscope with differential interference contrast optics, with reference to published floras (in particular, Krammer & Lange-Bertalot 1986; 1988; 1991; Vyverman 1991; and references outlined in Tibby 2001).

Diatom data are expressed as relative abundances of the diatom sum where all taxa, with the exception of the weakly silicified taxon *Rhizoselenia* sp. 1, abundant only in the uppermost sample, are included in the sum. Modified terms from Tibby (2001) were used to describe the relative abundance of diatom valves: trace (<1% relative abundance), minor (1–5%), important (5–20%), subdominant (20–50%), and dominant (>50%).

**CHIRONOMIDS**

Chironomidae are abundant in fossil records and have been used to trace the palaeoproductivity of lakes, to assess anthropogenic eutrophication and acidification, to monitor the impact of salinity fluctuations on benthic assemblages and, due to their sensitivity to temperature, in palaeoclimate reconstruction (Rossaro 1991; Walker et al. 1995; Dimitriadis & Cranston 2001). Sediment samples of 2 cm³ were extracted at c. 4 cm intervals down the core; given the limited sediment available for analysis, these do not correspond to the samples used for pollen and diatom analysis. Sample treatment followed Dimitriadis & Cranston (2001).

**NUMERICAL ANALYSIS**

To assess whether ordination techniques, which implicitly assume linear or Gaussian responses, should be applied, detrended correspondence analysis was used to determine the gradient length of the biological data sets (Birks 1998). All data sets had gradient lengths < 2.0, with the pollen and chironomid data sets < 1.0. Hence linear techniques (principal components analysis, PCA, and redundancy analysis, RDA) are appropriate. PCA is used to reduce the fossil biotic data to a two-dimensional plot and the resulting data set is displayed as a biplot for samples and taxa (Birks & Gordon 1985). PCA was performed using only those taxa whose percentage values exceeded 5% at least once. The data for each fossil group were square-root transformed to reduce the influence of very abundant taxa. Redundancy analysis was used to assess the effect of landscape disturbance and biomass burning (inferred from the inorganic and charcoal fractions, respectively) on all data sets. The influence of vegetation change on the lake ecosystem was assessed by determining the explanatory power of axes 1 and 2 of the pollen data on the diatom and chironomid data sets. The statistical significance of those variables was determined using 9999 Monte Carlo permutations of the ordination solution. RDA was performed where both pollen and diatom data were determined for each depth. However, for analysis of the chironomid data set, where adjacent data were not available, pollen data from the next available down core sample were utilized. All numerical analyses, with the exception of RDA, have been implemented within PSIMPOLL, a program for plotting pollen data, developed by Bennett (1994). Numerical zonation employed optimal splitting by sum-of-squares analysis to partition the stratigraphically constrained fossil assemblage data into significantly different zones (Bennett 1996). RDA was implemented in CANOCO for Windows 4.5 (ter Braak & Šmilauer 2002).

**Results**

**SEDIMENTATION AND CHRONOLOGY**

Figure 2(a) illustrates the two lines of best fit through the excess ²¹⁰Pb activity down core. Application of the CIC model to these alternatives provides a range of potential ages down core, estimating the lowest dated ²¹⁰Pb sample (46 cm) to be between 1850 AD and 1920 AD. The sequential first appearance of exotic pollen, Pb-210 and C-14 ages for the top 100 cm of sediment (year AD).
ages derived for each sample are likely to have greater uncertainties than represented by the envelope drawn around the preferred age-depth model due to the low resolution of age analysis points (Telford et al. 2004). The final age-depth model adopted for this study (Fig. 2b, solid line) is derived by linear interpolation between the key markers outlined in Table 2.

LOI% remains very high throughout the record (> 75% organics) showing minor inputs of inorganic sediment above 40 cm depth (Fig. 3c). Sedimentation rates are around 0.09 cm year\(^{-1}\) between 100 cm and 46 cm depth, increasing to 0.64 cm year\(^{-1}\) from 40 cm to 24 cm depth, and decreasing to 0.38 cm year\(^{-1}\) between 24 cm and the mud–water interface (Fig. 2b). Inorganic accumulation rates increase dramatically around 40 cm depth.

Zone P-1 (AD 1300–1880, 100–42 cm)

This zone is dominated by Elaeocarpus, Urticaceae/Moraceae, Cunoniaceae and Mallotus/Macaranga, with Agathis and Podocarpus attaining percentage values > 5% while percentage values of sclerophyll taxa and herbs are low. Fine and coarse charcoal particles are present throughout, with a series of small peaks in coarse charcoal deposition.Permanent open water conditions are indicated by the presence of Sparganium, Nymphoides and Botryococcus. The presence of swamp ferns from Thelypteridaceae (most likely Cyclosorus gongylodes, a weedy fern recorded in disturbed swampland) suggests a persistent floating mat habitat. The PCA shows Zone P-1 samples grouped on the negative side of Axis 1 aligned with dominant forest canopy taxa Elaeocarpaceae and Agathis.

Zone P-2 (AD 1880–1999, 42–0 cm)

This zone is separated from the preceding zone by the appearance of the exotic taxa Lantana, Mimosa, Plantago, Pinus, Solanaceae and Rumex, introduced during the period of European settlement, beginning in the early AD 1880s. Sclerophyll taxa maintain constantly low values whereas several rain forest taxa, including Urticaceae/Moraceae, Elaeocarpus and Agathis, show marked declines, most being removed as a result of selective

Fig. 3 Lake Euramoo pollen, spore, charcoal and sediment record. (a) Summary pollen diagram with dominant rain forest, sclerophyll woodland and introduced taxa. Thick horizontal bars after age-depth model indicate the positions of age determinations (dot ≤ 1% of total pollen sum). (b) % Diagram of rain forest, sclerophyll woodland and herbaceous taxa. (c) % Diagram of aquatics, ferns and other palynomorphs, with loss on ignition, inorganic sediment and charcoal accumulations rates.
logging during the late 19th and early 20th centuries (Birtles 1988). Increases are recorded in Rutaceae/Araliaceae, *Trema*, Cunoniaceae, *Sloanea* and *Eugenia*. Charcoal particle accumulation rates attain high values, although there is little apparent impact on the total rain forest taxa percentage of the pollen sum. The PCA shows Zone P-2 samples grouped on the positive side of Axis 1, aligned with disturbance taxa such as *Trema*, *Lantana* and grasses.

**DIATOMS**

See Figs 5 and 6.

**Zone D-1 (AD 1300–1720, 100–62 cm)**

Zone D-1 is characterized by high relative abundances of *Eunotia pectinalis*. *Aulacoseira* sp. 1 is important lower in this zone but, after peaking to dominance at 80 cm, it is replaced by *Eunotia* aff. *implicata* and *Gomphonema gracile*, while *Cyclotella* aff. *glomerata* has a notable peak at 76–72 cm. The separation of Zone D-1 samples to the positive side of axis 1 on the PCA is driven by the dominance of *Eunotia pectinalis*.

**Zone D-2 (AD 1720–1850, 62–46 cm)**

In D-2, *Aulacoseira* sp. 1 replaces *Eunotia pectinalis* as the dominant diatom taxon in the Euramoo record. *Gomphonema gracile* is more abundant in this zone, though it does not reach subdominant proportions. The combined presence of *Staurosira construens* f. *venter*, *Staurosirella elliptica* and *Staurosirella pinnata* at minor to important representation in the 56-cm sample is notable. In the upper samples in this zone, *Aulacoseira ambigua* occurs above 2% for the first time in the record. The shift in sample grouping to the negative side of axis 1 in the PCA is driven by the shift to dominance of *Aulacoseira* sp. The strong negative values on axis 2 reflect peak values being reached in *Gomphonema gracile* and *Eunotia* aff. *implicata*.

**Zone D-3 (AD 1850–1950, 46–12 cm)**

Zone D-3 is characterized by continued reduction of *Eunotia pectinalis*, although, unlike D-1 and D-2, there are no corresponding changes in *Aulacoseira* sp. 1. *Cyclotella* aff. *glomerata* exhibits a variable, gradual increase through the zone. *Gomphonema gracile* and *G. parvulum* are important taxa, which reach their greatest...
abundance in this zone. There is a minor shift in sample distribution in the PCA towards the negative side of axis 1, where a range of minor taxa, including Encyonema gracilis and Gomphonema parvulum, reach maximum percentage values.

Zone D-4 (AD 1950–1999, 12–0 cm)

Aulacoseira sp. 1 has a higher mean relative abundance in zone D-4 than in other zones. Aulacoseira ambiguа and Cyclotella aff. glomerata are also at
their most abundant in this zone, with the latter peaking in the youngest two samples in the record. In this zone, *Eunotia pectinata* is all but eliminated from the record, as are *Gomphonema gracile* and *G. parvulum*. Peak values in *Cyclotella aff. glomerata*, *Aulacoseira ambiguus* and *Fragilaria sp.* shift the sample grouping in the PCA towards the positive side of axis 1.
Zone C-1 (c. AD 1300–1955, 104–14 cm)

Zone C-1 is characterized by consistent dominance of Monopelopia sp., Procladius paludicola, Chironomus sp. 1 and Dicrotendipes jobetus. Djamabatista sp., Chironomus sp. 2, Microtendipes umbrosus, Polypedilum leei, P. nr serosum and Zavreliella marmorata are found only in this zone, and only at low levels. Parakiefferiella sp. percentage values begin to increase towards the top of this zone (after AD 1920). The separation of Zone C-1 samples to the negative side of axis 1 in the PCA is driven by the dominant taxa, particularly Dicrotendipes jobetus.

Zone C-2 (AD 1955–1999, 14–0 cm)

Parakiefferiella sp. percentage values continue to increase in this zone, becoming dominant by the surface sample. Monopelopia sp., Procladius paludicola and Chironomus sp. 1 remain common taxa, whereas Dicrotendipes jobetus decreases. Xenochironomus sp. also increases to peak values. Polypedilum K 1 is present only in this zone. The shift of sample grouping to the positive side of axis 1 in the PCA is due to the increased dominance of Parakiefferiella sp. and Xenochironomus sp. at the expense of other common chironomid taxa.

Interpretation and discussion

Historical and palaeoecological analysis of ecosystem change attempts to extend the range of spatial and
temporal perspectives, beyond those attainable with only ecological data, on the environmental drivers and disturbance processes that interact to control patterns and change in biotic assemblages. A single coring locality (Lake Euramoo) provides a window into both the terrestrial environment, through pollen and charcoal, and the aquatic environment, through pollen, chironomids and diatoms. Each assemblage reflects environmental changes at different spatial scales and can provide a greater understanding of the pre-European and European history of natural and human disturbance, environmental change and catchment ecosystem dynamics.

**TERRESTRIAL ENVIRONMENT**

Lake Euramoo has a surface area of approximately 4.4 ha, which should receive pollen from within a < 100 m to 10 km radius (assuming that the general pollen dispersal model of Jacobson & Bradshaw 1981 is applicable in the tropics). The dominant contribution will be from the local (< 100 m) to extra-local (100–1000 m) taxa and, as these will be mainly those contained within the crater, the data will provide a detailed history of vegetation dynamics within the catchment. The pollen record shows that the composition of rain forest in this region has not been stable over the last 700 years (Figs 3 and 4). The occurrence between the 13th and 19th century, of only minor fluctuations in the dominant rain forest taxa Elaeocarpus, Mallotus/Macaranga and Urticaceae/Moraceae appears to reflect a stable rain forest environment. Periodic fire events during the early part of the record (13th to 16th century) may reflect a potentially higher level of disturbance in the rain forest or at the rain forest-sclerophyll margin, but fire events seem to have been suppressed at both regional and local level between the 17th and 19th century. The most significant change in the pollen record occurs at AD 1880, and includes the reduction of key taxa in the pollen record, such as Agathis and Podocarpus (both exploited for the timber industry during the late 19th and early 20th century), the sequential appearance of exotic taxa Lantana, Mimosa, Plantago, Pinus, Solanaceae and Rumex, and increased charcoal accumulation. These rapid changes coincide with the onset of European occupation and are most likely the result of clearance and burning activities associated with the timber and farming industry between about AD 1880 and 1920. Their impact appears to have persisted through to the present, even after the cessation of logging and clearance activity in the 1950s. While there are no significant zonal changes identified in the pollen record of the post-European settlement period, invasions of exotic taxa continue to the present.

**AQUATIC ENVIRONMENT**

The ability to reconstruct precisely the aquatic history of Lake Euramoo is hampered by the absence of dedicated biotic data sets from northern Australian lakes, and a lack of species-level identifications. Despite this, much information can still be gleaned for key taxa. In particular, we infer general water quality shifts from southern Australian diatom and chironomid data sets (e.g. Dimitriadis & Cranston 2001; Tibby et al. 2003) and changes in the nature of the physical lacustrine environment from habitat preferences of key taxa (e.g. plant associated vs. planktonic).

The diatom record exhibits the greatest variability of the proxy data sets, with the major change being the switch in dominance between *Eunotia pectinalis* and *Aulacoseira* sp. 1 that occurs between 64 and 60 cm, clearly predating European arrival (see Fig. 2b and below). However, a further, longer record from Lake Euramoo indicates that levels of these two taxa were variable over at least the thousand years before European arrival (J. Tibby, unpublished data). Hence, although lowered values of *E. pectinalis* predate European influence, the early fall might merely reflect natural variability, which is compounded by suppression as a result of European arrival.

The next substantial change in the diatom record occurs between 42 and 46 cm (i.e. the zone D-2 and D-3 boundary). Given that the pollen of introduced *Lantana* first appears at 40 cm and pollen of introduced taxa may
post-date the first evidence of European-induced water quality change (Leahy et al. 2005), it seems likely that this change is due to European impact. Indeed, the first definitive evidence of European arrival appears to be registered in the sample immediately below the zone boundary (46 cm). Staurosira construens f. venter, Staurosirella elliptica and Staurosirella pinnata exhibit relatively minor but distinctive peaks at this depth. These taxa make up 17% of the diatom sum at this point, whereas they are always less than 0.5% of the count for all other samples.

These taxa are associated predominantly with alkaline waters (Bennion 1995; Sayer 2001), often with high turbidity (Gell et al. 2002). In south-eastern Australia they have pH optima of 7.7 (Staurosira construens f. venter), 8.2 (Staurosirella pinnata) and 8.6 (Staurosirella elliptica) (Tibby et al. 2003 and unpublished data). The preference for alkaline waters contrasts with the optimum for the dominant pre-European diatom Eunotia pectinalis (6.9) and suggests an increase in pH.

In south-eastern Australia, increased pH has been observed in several riverine aquatic systems shortly after European arrival (Reid et al. 2002; Tibby et al. 2003; Gell et al. 2005). This increase is attributed in part to an increasing load of base cations due to catchment erosion (Tibby et al. 2003), a process that may in itself be caused by fires (Korhola et al. 1996). A similar phenomenon may have occurred at Lake Euramoo. Certainly there is a general association between increased macrocharcoal in the post-European phase and the reductions in Eunotia pectinalis. However, as the redundancy analysis suggests (Table 3), the effects of burning on lake pH are likely to be indirect. The sustained reduction of E. pectinalis from the record suggests that elevated pH may have persisted as a result of deforestation and its tendency to raise soil pH in the region (Rasiah et al. 2004).

Associated with the decline of Eunotia pectinalis are zone D-2 increases in Aulacoseira ambiguca and Gomphonema parvulum, which are competitive in elevated nutrient environments. The abundance of these taxa indicates a notable enrichment of the lake waters in the post-European phase. The rise in the aquatic microphyte Sparganium during this phase might also relate to nutrient enrichment in the lake margin habitats. The most likely source of these nutrients would be localized catchment erosion resulting from the activities of timber cutters and, certainly, increases in the delivery of inorganic material (Fig. 3c).

The diatom and chironomid communities show an apparently strong response to the cessation of logging and clearance activities in the region, with a number of significant taxa changes at the top of zone D-1 (Fig. 5) and zone C-1 (Fig. 7). The elimination of the diatoms Eunotia aff. implicata, Fragilaria tenera and Gomphonema gracile and the nutrient rich indicator Gomphonema parvulum, result largely from increases in Aulacoseira sp. 1 and Cyclotella aff. glomerata. The rise in the chironomid Parakiefferiella sp. and Xenochironomus sp. and the reduction in Dirotendipes jobetus and Tanypus nr fascithorax at the same time represent the most significant shift in chironomid assemblages over the preceding 600 years. Xenochironomus sp. is known to be closely associated with decaying wood and these general trends may indicate a shift towards expanding littoral habitats. Unfortunately the ambiguous taxonomy and lack of ecological data for these taxa makes the precise reason for these changes elusive.

MAGNITUDE, DIRECTION AND INTERACTIONS IN ECOSYSTEM CHANGE

Did European land-use activity represent an unprecedented event that lay outside the historic range of variability? The pre-contact pollen, diatom and chironomid records indicate a degree of variability on centennial time-scales, with, for example, periods of dominance by the acidic periphytic diatom taxon Eunotia pectinalis in the 13th, 14th and 17th centuries interspersed with periods of dominance by Aulacoseira sp. 1 in the 15th and 18th centuries, and similar amplitude variation in the pollen and chironomid records. The rain forest and diatom communities appear to rapidly register the first effect of European arrival, with the boundary between zones D-2 and D-3 and P-1 and P-2 located very close to the known historical first European occupation event.

An historic range of variability perspective (Morgan et al. 1994) is one way of examining the proposition that the impact of European land-use on rain forest ecosystems lies outside the known range of variability in terms of extent and severity. In Fig. 9 we use the first and second axis of the PCA as a proxy for biotic variability through time. All 1st axis PCA curves indicate that unprecedent changes do occur during the European period although these are neither unidirectional nor synchronous. The strong and sustained shift in rain forest and algae community composition beginning at the time of European settlement implies that the community response was rapid and related, at least in part, to burning and sediment mobilization in and around the catchment. However, not all aspects of the lake catchment ecosystem were as sensitive: the first axis of the chironomid record and all second axes show a much delayed or benign response to European settlement. Redundancy analysis of these data sets shows that catchment–lake interactions are implicated in aquatic community perturbation (Table 3). Major shifts in vegetation (as summarized on PCA axis 1 of the pollen data) explain a significant (P < 0.05) and substantial amount of variation in both the diatom (16.6%) and chironomid (10.7%) data. A stronger influence of vegetation change on the algal community is implicated as axis 2 of the pollen PCA also explains a significant amount of diatom variance (8.6%, P = 0.02). This may be due to the more direct relationship between diatoms and water quality (Brooks et al. 2001), although the sample offset between the two indicators may play a role.

The Lake Euramoo catchment has been protected from clearance and burning activity since the 1950s due to designation of National Parks and the establishment of...
CLIMATE CHANGE AND IMPLICATIONS FOR THE FUTURE

How has climate change influenced terrestrial and aquatic ecosystems and what impact might it have on the future of the rain forest environment? Recent high-resolution pollen and charcoal records from Lake Euramoo (Haberle 2005) show that climate change has influenced rain forest dynamics on millennial and century timescales. A sustained onset of increased burning around Lake Euramoo after 5000 BP is accompanied by evidence for greater disturbance of the rain forest, suggesting that fires were occurring at a frequency sufficient to result in an opening up of the canopy. These changes may have been driven by overall drier conditions or increased rainfall seasonality associated with intensified El Niño activity after c. 5000 yr (Kershaw & Nix 1988; Haberle et al. 2001; Hayne & Chappell 2001). Given the emerging archaeological evidence for human activity at this time, it is likely that the fire record is a result of human intervention overlaying these climatic influences (Cosgrove 2005; Haberle 2005). 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 & David 2004).

On shorter time-scales, and during the last millennium, our understanding of north-east Australian climate change is limited to high resolution data from coral growth records, where Hendy et al. (2002) infer persistent elevated sea surface temperatures in the SW Pacific throughout the Little Ice Age (17th–19th centuries) compared with the 20th century. However, a conflicting sea surface temperature record has been derived from coral in New Caledonia, suggesting a 1.4 °C cooling around AD 1730 (Crowley et al. 1999). It has been postulated that the apparent regional differences in the temperature records for the Little Ice Age are the result of significant shifts in the ocean-atmosphere system during this period, with temperature gradients between tropical low latitudes and mid-to-high latitudes being greater during the Little Ice Age (Hendy et al. 2002). For the Atherton Tableland this may have produced higher rainfall in a low amplitude El Niño period (D’Arrigo et al. 2005). The evidence from Lake Euramoo seems to confirm this LIA climate scenario, with the combination of low charcoal accumulation and low open forest-disturbance taxa in the rain forest pointing to wetter conditions and possibly muted interannual climate variability (El Niño, Southern Oscillation) during the 17th to 19th century.

Clearly temperatures, rainfall and the amplitude and frequency of El Niño-related climate variability have fluctuated through time and space in the region. At the time of European arrival on the Atherton Tableland, the region appears to have been entering a period of heightened climate variability, with severe droughts (e.g. Australia’s Federation Drought of 1895–1902) coinciding with the early settlement period and thus exacerbating the impact of human activity on a previously very wet and relatively stable environment. The combined impact of these climate and land-use changes led to an unprecedented shift in rain forest community composition that still persists, despite 50 years of protection. It therefore seems unlikely that ongoing protection and management will allow rain forest habitats to return to a pre-European state, particularly given that future climate change is expected to bring about further shifts in rain forest habitat distribution and loss of key vertebrate species (Williams et al. 2003). This supports the notion that ecological and climate thresholds are not necessarily the same, and the effects of crossing them are not necessarily reversible (Maslin 2004).

Conclusions

Pre-European rain forests on the Atherton Tableland were highly dynamic, responding to climate change at a range of time-scales (millennium to decades), as well as to fire-related disturbance and Aboriginal activity. The response of both terrestrial and aquatic ecosystems to European settlement in the region was rapid and profound, and was most likely driven by changes in fire regime and by forest clearance. The loss of diversity may have led to an irreversible switch to an alternative state.

Future research should include studies of local environmental change in similar small catchments in order to compare species and community responses to the European settlement event on the Atherton Tableland. Retrospective studies of the historic range of variability of forest and aquatic ecosystems and fire may provide at least tentative answers to the three key questions that can then inform management decisions and resource planning.

Acknowledgements

The authors wish to thank Peter Kershaw for encouraging this work. Nick Porch and Ainsley Noakes helped with fieldwork. Andy Moores prepared the diatom samples. Roger Flower and Patrick Riaoul provided useful diatom taxonomic advice. Permission to core at Lake Euramoo was granted through the Queensland Parks and Wildlife Service, Queensland Government. Radiocarbon and Lead-210 analysis was completed at the Australian Nuclear Science and Technology Organization funded through an AINSE Grant 00/60. S.H. was supported by an Australian Research Council QEII Fellowship at Monash University and the Australian National University. J.T. was supported by an Australian Research Council grant. S.D. was supported by an Australian Postgraduate Award.

References


