Evidence for catastrophic shifts in the trophic structure of flood-plain lakes associated with soil erosion

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Abstract The introduction of European agricultural practices to southeastern Australia during the 1800s was associated with a period of extensive erosion in upland areas. The effects of this erosion on aquatic systems were substantial. Deep gullies replaced natural "chain of ponds" systems in headwaters, and the resultant "sand slugs" reduced substrate complexity and stability in middle reaches. The impact of this period of intensive erosion in lowland reaches is less obvious. This study presents the results of palaeoecological reconstructions from several flood-plain lakes on the Murray River that cover the period prior to the introduction of agriculture to the present. These records show a consistent pattern whereby benthic algae are replaced by planktonic algae concomitant with peaks in indicators of high sediment input. This pattern supports studies which have utilised different indicators at other sites in the region and is interpreted as resulting from light attenuation due to high suspended-sediment loads during a phase of intensive sediment erosion and transport during the mid to late 1800s. The maintenance of this macrophyte-free state in the absence of continued high sediment loads up to the present day is thought to reflect the existence of "alternative stable states" in these systems.

Key words erosion; flood plains; billabongs; aquatic plants; diatoms; palaeolimnology

INTRODUCTION

The introduction of European agricultural practices across the temperate regions of the Australian continent during the late 18th and 19th centuries led to profound landscape changes. The dispossession of indigenous people, changed fire regimes, the removal and thinning of forest and woodland vegetation communities and introduction of exotic flora and fauna combined to transform the Australian landscape. These factors all contributed to a range of environmental impacts that were experienced well before any attempts to understand the structure and function of Australia's ecosystems began in the middle of the 20th century. As a consequence, our understanding of the degree, timing, and proximate causes of these early post-settlement changes is largely based on fragmented and often cryptic evidence.

River systems were also substantially impacted by the dramatic changes in land use that occurred through the middle to late 19th century in southeastern Australia. Deep gullies are widespread in upland areas and are believed to have resulted from severe erosion associated with clearance of native vegetation in upper catchments (Prosser *et al*., 2001). These gullies are thought to have replaced natural "chain of ponds" systems in headwaters (Prosser & Winchester, 1996). Sediments from these gullies have been deposited as "sand slugs" in the middle reaches, reducing the complexity and stability of stream beds that were formerly characterised by more heterogeneous substrates. Sand slugs can have a significant impact on stream biota through loss of habitat (Rutherfurd, 2000; Prosser *et al*., 2001), and through the greater vulnerability of communities within the less stable sandy substrates to disturbance during spates (O'Connor & Lake, 1994).

The impact of this period of intensive erosion on the lowland reaches of Australian rivers and the ecosystems they support is less obvious. However, recent palaeoecological studies of meander cutoffs (known as billabongs in Australia) on lowland reaches of rivers in southeastern Australia have provided evidence that the period of intense erosion did have severe impacts on these ecosystems (Ogden, 2000; Reid *et al*., 2002; Tibby *et al*., 2003; Reid *et al*., 2007). These studies used macrofossil and diatom stratigraphies to reconstruct ecological changes in several billabongs over the past few hundred years. They showed that while the billabongs are currently largely devoid of submerged macrophytes, they appear to have supported abundant submerged macrophyte communities prior to the arrival of Europeans. Ogden (2000) suggested that the apparent loss of macrophytes was linked to the severe rates of soil erosion during the late 1800s that are indicated by geomorphological evidence from the region (Erskine *et al*., 1993; Prosser *et al*., 2001). Ogden (2000) hypothesised that the high sediment loads associated with severe erosion may have reduced photic depth in the billabongs sufficiently to cause macrophyte loss.

This paper presents some results from a study that investigates how widespread this purported loss of macrophytes was, and the supposed link with high sediment loads. This is achieved through palaeoecological reconstruction of several billabongs on the flood plain of the Murray River in southeast Australia.

Study area

Sediment cores were collected from five billabongs situated on the Murray River flood plain approx. 30–45 km downstream of the Hume Weir, the principal flow regulation structure for the middle Murray (Fig. 1). The region is relatively dry and warm. Mean maximum temperatures in January and July are around 30ºC and 15ºC, respectively, while the corresponding minima are 15ºC and 0ºC. Annual rainfall is around 600 mm, but this is exceeded greatly by potential evaporation, which stands at 1586 mm at Rutherglen (approx. 10 km to the west) (Australian Bureau of Meteorology, unpublished data).

Flows in the Murray River are regulated to supply water for irrigation. In the study reach the main effect of this regulation is a seasonal flow reversal (Maheshwari *et al*., 1995), whereby flows in winter and spring are now reduced from normal as water is held in the Hume Weir. Flows in summer and early autumn are subsequently increased from normal when this water is released to supply downstream irrigators. Three of the five billabongs included in this study (Iona 1, Iona 2 and Hogan’s 3) receive water directly from the river during these high summer flows, while the remaining two billabongs (Hogan’s 1 and Hogan’s 2) fill at discharges higher than the summer irrigation flow. Of the five billabongs, only Hogan’s 2 currently supports submerged macrophytes, with scattered occurrence of *Ceratophyllum*, *Myriophyllum* sp. and *Potamogeton tricarinatus*.

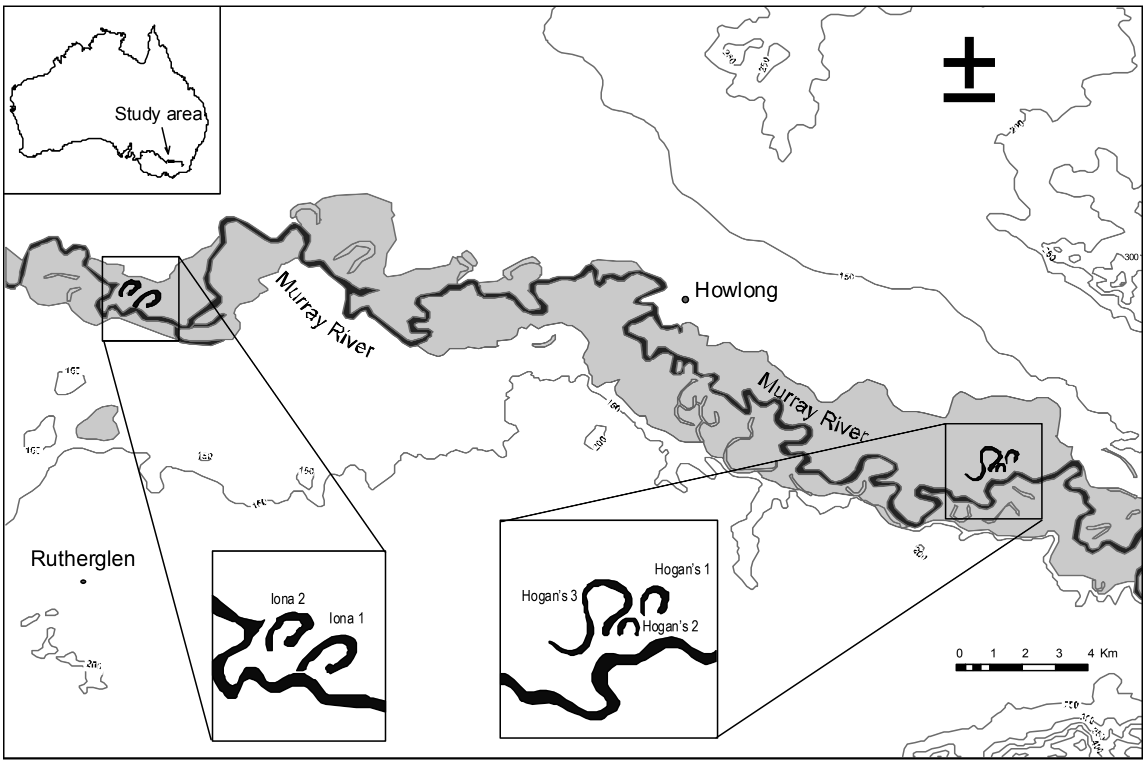

Fig. 1 Location of study billabongs.

METHODS

Cores were taken at each billabong from the deepest area of the basin, as detected by informal bathymetric survey. Coring at Hogan's 2, Hogan's 3, Iona 1 and Iona 2 was carried out in February 2001, using a piston coring system utilising 50 mm internal diameter PVC piping which sampled sediment in continuous lengths. Coring at Hogan's 1 was carried out in July 2000 using a Livingstone system with a 1 m core tube and 20 cm overlap between drives.

Upon return to the laboratory, magnetic susceptibility of the cores was measured using a Bartington MS Series One TM meter core scanning loop sensor. All cores were sampled at 8 cm intervals for percentage water content, and percentage Loss-On-Ignition (LOI) and diatom analysis. Finer resolution sampling, specifically for diatom analysis, was also carried out on parts of the remaining length that corresponded to substantial compositional changes as identified in preliminary analyses. Additional sampling was also carried out at Hogan's 1 for pollen and macrofossils; however, the results of these analyses are reported elsewhere (Reid *et al*., 2007).

Sub-samples of 1 cm^3 from each sediment sample were used for diatom analysis. Preparation entailed oxidation with dilute hydrogen peroxide (10%) in a water bath at 70ºC for 2 h, or until obvious organic residue had been removed. Samples were then rinsed by repeated washing with distilled water. Following oxidation, sub-samples were mounted on coverslips using Naphrax. The total proportion of the original sample mounted on each coverslip was recorded to allow for diatom valve concentrations to be calculated. Diatom counts were made with a Zeiss Axioskop at 1000× magnification. A total of at least 300 valves were counted for most samples. Species abundances are represented as a percentage of the full assemblage for each sample. Concentrations of diatoms per mm^3 in each sample were estimated by dividing the total count by the proportion of the sample scanned. Detailed diatom analysis was carried out on three of the five cores – from Hogan's 1, Hogan's 2 and Iona 2. Samples from Hogan's 3 and Iona 1 were only scanned to establish trends relative to those revealed by the detailed analysis of the remaining cores.

Moisture content of sediment samples was determined gravimetrically by oven drying at 105ºC for 24 h. The dried samples were then weighed before and after ignition at 550ºC for 2 h to determine LOI as a proxy for organic content. Samples of bulk sediment were taken from the base of the cores from Hogan's 1 and Iona 2, as well as from a depth of 170 cm in Iona 1, for AMS ^{14}C dating at the University of Waikato Radiocarbon Dating Laboratory. In preparation for dating, samples were washed in hot 10% HCl, rinsed and treated with hot 1% NaOH. The NaOH insoluble fraction was treated with hot 10% HCl, filtered, rinsed and dried. Dates are reported as conventional ages (Stuiver & Polach, 1977).

RESULTS

The stratigraphy of the billabong sediments is relatively consistent across cores. The lowermost sediments of each core typically contain the greatest sand content, suggesting they were deposited under higher energy conditions, perhaps due to higher connectivity with the mainstream. These sand-rich sediments are overlain in four of the five cores by more organic sedimentary units (Fig. 2), suggesting a transition to lower energy, higher productivity conditions consistent with the development of predominantly lentic billabong environments. The sediments overlying the organic-rich units are more consolidated and contain fine sands. These units are also characterised in all cores by a large peak in magnetic susceptibility (Fig. 2). Above the magnetic susceptibility peak, all cores are characterised by a relatively uniform organic lake mud that continues to the surface.

Diatom stratigraphies of three cores on which detailed diatom analysis was carried out are presented in Figs 3–5. As for the physical stratigraphy, there is consistency in the diatom records from Hogan's 1, Hogan's 2 and Iona 2. In each case, diatom valves are either absent or very sparse in the lowermost sediment unit. Diatom valve concentrations are higher in the organic-rich sediments overlying the sandy basal unit and are dominated by attached littoral diatoms (Figs 3–5). In contrast, the consolidated sediments corresponding to the magnetic susceptibility peaks are dominated in each core by motile littoral diatoms and aerophilous, or soil-dwelling diatoms (Figs

3–5). Finally, the surface units in each core are dominated by planktonic diatoms. Scans of processed sediments from Hogan's 3 and Iona 1 showed that planktonic diatoms also predominated in the organic lake mud unit, but were rare in the underlying units.

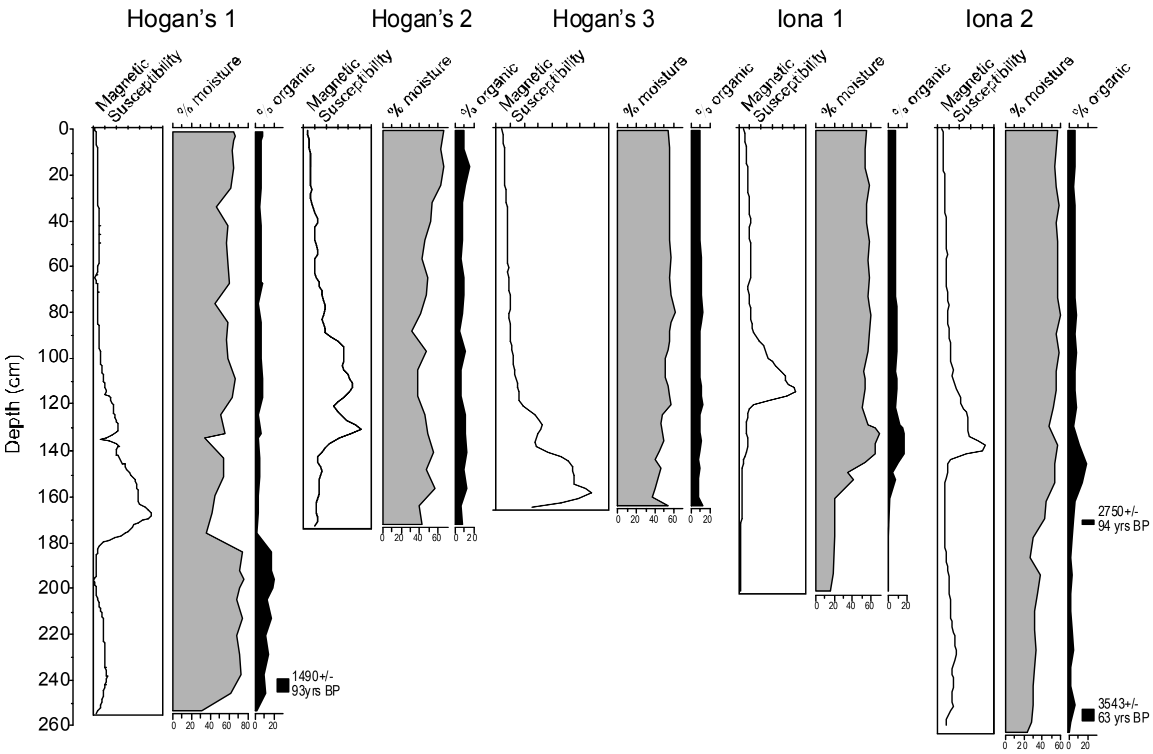

Fig. 2 Magnetic susceptibility, moisture, and organic content of sediment cores from the five study billabongs.

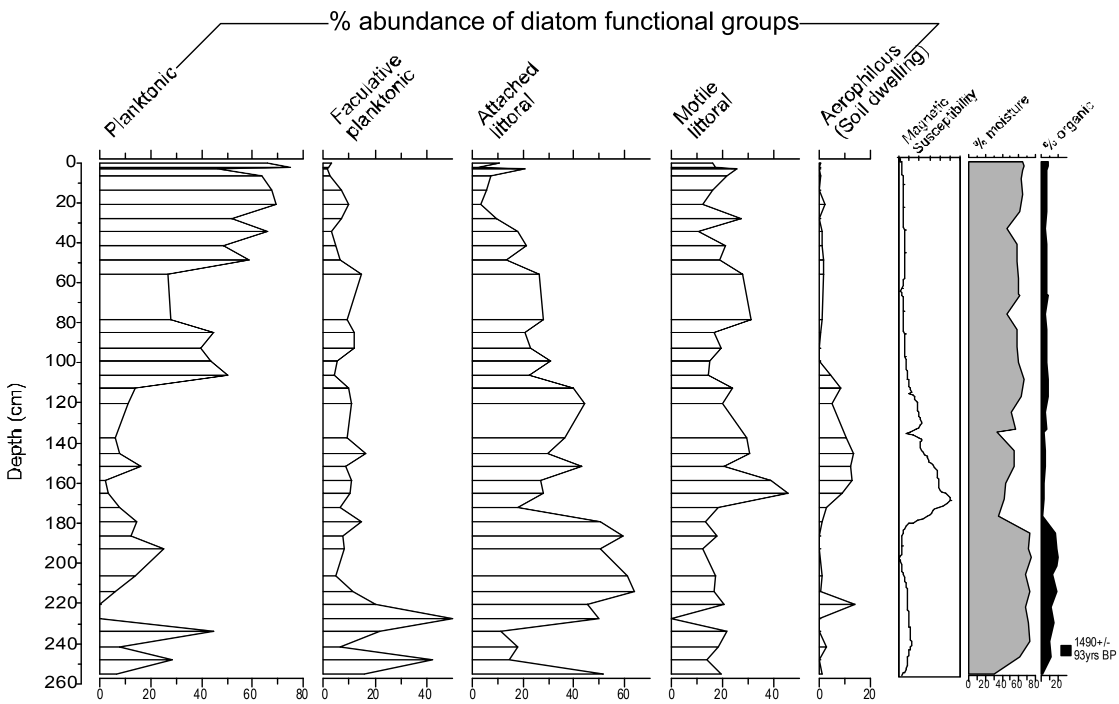

Fig. 3 Stratigraphic changes in the abundance of diatom functional groups in the sediment record from Hogan's 1 Billabong.

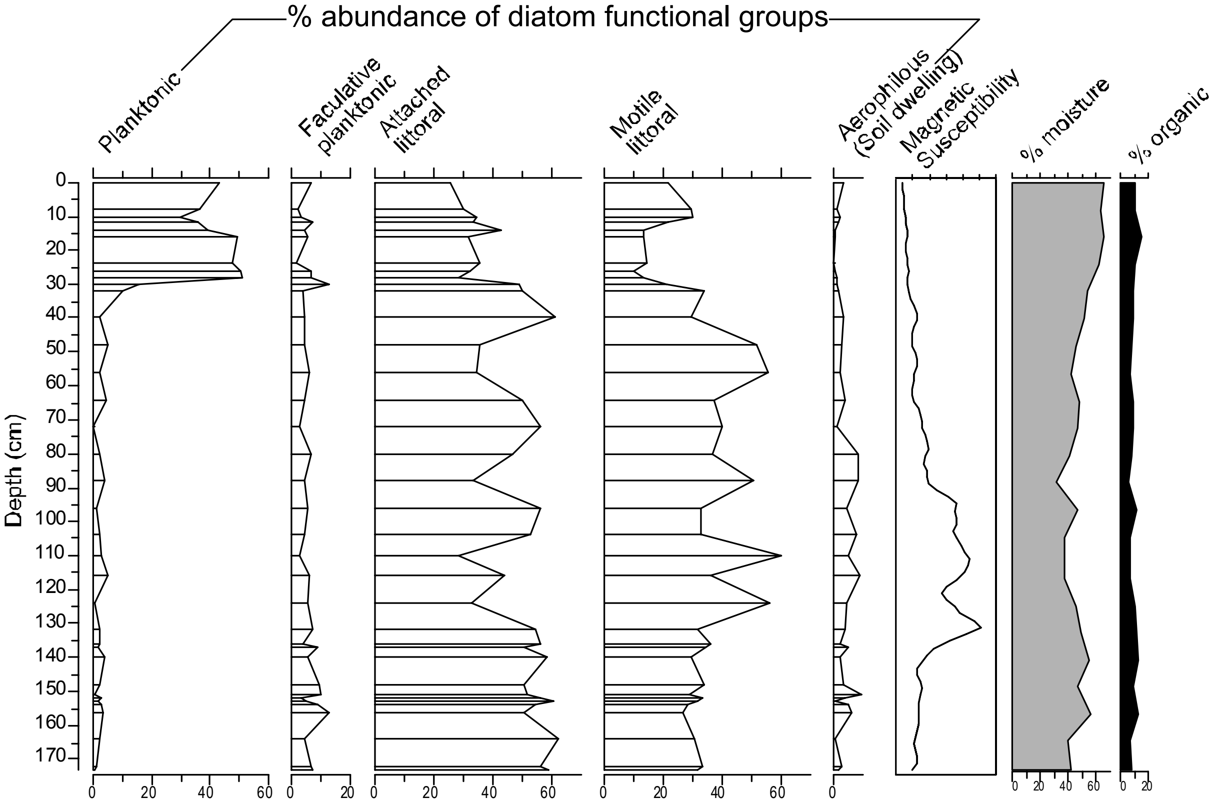

Fig. 4 Stratigraphic changes in the abundance of diatom functional groups in the sediment record from Hogan's 2 Billabong.

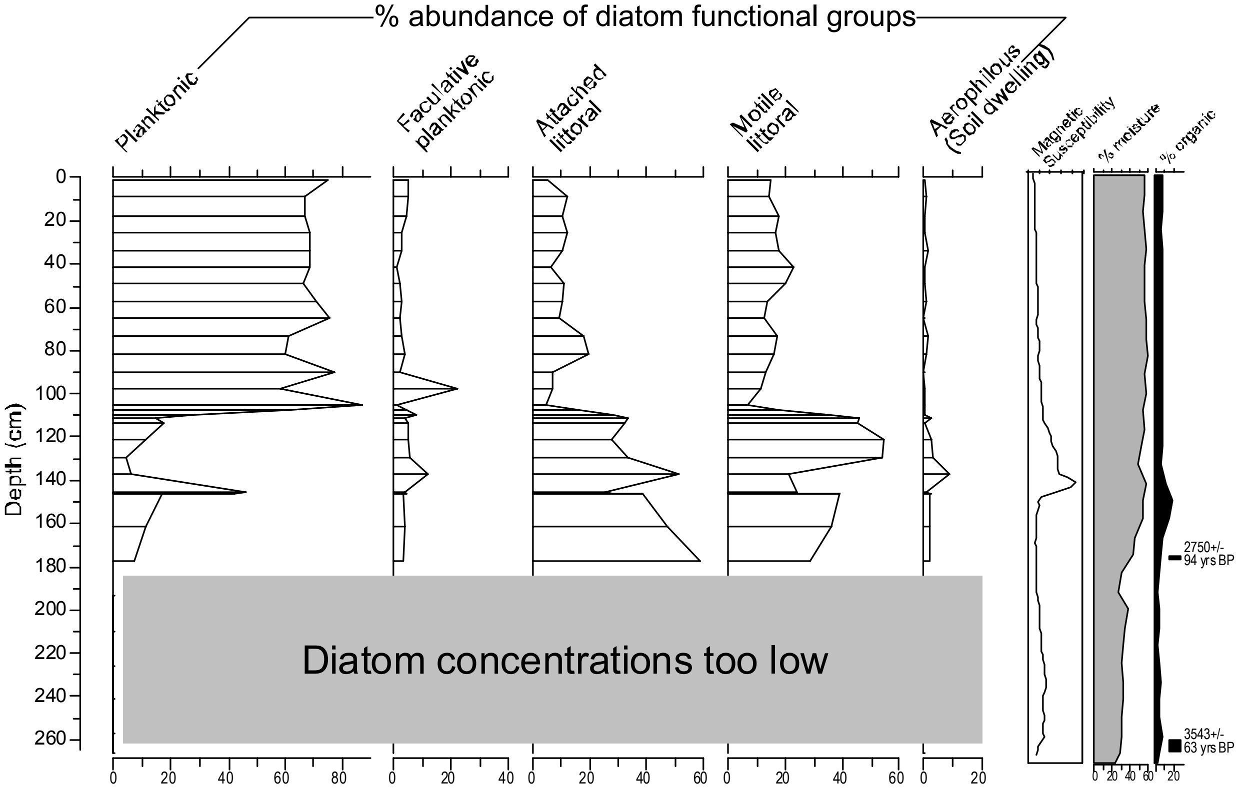

Fig. 5 Stratigraphic changes in the abundance of diatom functional groups in the sediment record from Iona Billabong.

DISCUSSION

The stratigraphic records obtained from the five billabongs in this study are notable for the consistency in the patterns they exhibit. In the lowermost portions of the sequences, basal material is characterised by a greater sand content, indicative of higher energy conditions, such as would be expected prior to the partial or complete abandonment of the channel. The sequences subsequently show a gradual upward fining of the sediments and a corresponding increase in organic material content. This change can be attributed to the gradual development of littoral emergent and submerged vegetation communities in the billabongs under lentic conditions, an interpretation that is reinforced by the abundance of attached diatom species in these organic-rich sediments (Figs 3–5). Thus, the lowermost portions of the sediment records all show a pattern that is consistent with a transition from a high-energy river channel to a low energy and productive lentic environment, and support the assertion of Ogden (2000) that aquatic macrophytes were more abundant in billabongs such as these in the recent past.

Perhaps the most striking feature of the stratigraphic records from the five billabongs, however, is the consistent presence of distinct peaks in magnetic susceptibility in each record at depths of around 170 cm to 120 cm (Fig. 2). It is likely that these magnetic susceptibility peaks resulted from a high rate of input of eroded material during this time (Dearing, 1999; Eriksson & Sandgren, 1999), an interpretation that is supported by corresponding peaks in the abundance of aerophilous or soil dwelling diatoms (Tibby, 2001) (Figs 3–5). The diatom records from Hogan's 1, Hogan's 2 and Iona 2 suggest that this period of high sediment input had a dramatic effect on these billabong ecosystems. Immediately above the peaks, the relative abundance of attached diatoms declines, which in turn suggests a decline in the abundance of aquatic plants. Although a causal link cannot be assumed, it would seem likely that one exists through the mechanism of high turbidity and reduced photic depth (Ogden, 2000). Sometime later in the record, planktonic diatoms become more abundant, suggesting that the event led to a shift in state from macrophyte to plankton dominance.

The consistency in the pattern across all billabongs suggests that this event had a widespread impact and was regionally synchronous. While the timing of the observed changes is less certain, the balance of probabilities is that the postulated period of high sediment influx occurred in the mid to late 1800s. This assertion is based on ^{210}Pb dating and the appearance of exotic pollen in the Hogans's 1 record, which suggest that the peak in magnetic susceptibility occurred around 1850 AD (Reid *et al*., 2007).

The results of this study suggest that soil erosion had a dramatic impact on the aquatic ecosystems of the lowland reaches of Australian river systems, leading to a widespread and apparently synchronous transition from macrophyte to plankton-dominance in many flood-plain lakes. Furthermore, the results highlight the early and widespread impact of European land-use practices on river ecosystems after their introduction to the Australian continent.

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