

Fire regime and vegetation change in the transition from Aboriginal to European land management in a Tasmanian eucalypt savanna

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Abstract. Using pollen and charcoal analysis we examined how vegetation and fire regimes have changed over the last 600 years in the Midlands of Tasmania. Sediment cores from seven lagoons were sampled, with a chronology developed at one site (Diprose Lagoon) using ²¹⁰Pb and ¹⁴C dating. Statistical contrasts of six cores where *Pinus* served as a marker of European settlement in the early 19th Century and showed significant changes in pollen composition following settlement with (a) influx of ruderal exotic taxa including *Plantago lanceolata* L., Brassicaceae, Asteraceae (Liguliflorae) and *Rumex*, (b) increase in pollen of the aquatics *Myriophyllum* spp. and Cyperaceae, (c) a decline in native herbaceous pollen taxa, including Chenopodiaceae and Asteraceae (Tubuliflorae) and (d) a decline in *Allocasuarina* and an initial decline and then increase of Poaceae. The presence of Asteraceae (Liguliflorae) in the pre-European period suggests that an important root vegetable *Microseris lanceolata* (Walp.) Sch.Bip. may have been abundant. Charcoal deposition was low in the pre-European period and significantly increased immediately after European arrival. Collectively, these changes suggest substantial ecological impacts following European settlement including cessation of Aboriginal traditions of fire management, a shift in hydrological conditions from open water lagoons to more ephemeral herb covered lagoons, and increased diversity of alien herbaceous species following pasture establishment.

Additional keywords: Aboriginal fire management, grassland, grassy woodland historical ecology, landscape ecology, macro-charcoal, palynology.

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Introduction

The transition from Aboriginal to European management is a critical period in the history of Australian ecosystems. European colonisation of Australia, which commenced in 1788, resulted in the introduction of new plants, animals and microorganisms, some of which initiated a wave of native plant and animal extinctions (MacPhee and Flemming 1999; Woinarski *et al.* 2015). Aboriginal people were removed from their traditional lands causing the loss of ancient socio-ecological systems, and native vegetation was modified for farmland, urban areas and mines (Fensham 1989; Lunt 1991). Particularly hard hit were temperate environments, especially those dominated by native grasslands and woodlands with a grassy understorey that collectively form a savanna biome. These regions were ideal for early pastoral settlement, which lead to rapid changes in land management (Benson and Redpath 1997). The oldest agricultural landscapes in Australia are woodlands on the Cumberland Plain to the west of Sydney, settled in 1791, and the Midlands of Tasmania settled from the early 1820s (Phillip 1892; Morgan 1992). The conversion of temperate grassland and

woodland ecosystems, which we collectively describe as 'temperate savanna', has been almost complete with less than 20% of these ecosystems remaining on mainland Australia and Tasmania (Kirkpatrick *et al.* 1988; Fischer *et al.* 2009).

There are sparse data on Aboriginal land use practices in temperate savannas given that these ecosystems were impacted so early in the colonial historical of Australia. Archaeological evidence has illuminated patterns of Aboriginal land occupancy and there are early colonial reports of Aboriginals burning the landscape; however, the ecological consequences and frequency of burning is unclear (Kee 1990; Brown 1991). Aboriginal land management continues with relatively little disruption in tropical Australian savannas but there is uncertainty about the applicability of these contemporary management practices in to temperate Australian systems (Bowman 1998; Russell-Smith *et al.* 2013). For these reasons, prehistorical reconstructions of Aboriginal land management regimes are of prime importance in these temperate ecosystems.

Broadly, there are two different approaches to reconstruction of past environments: environmental history, stemming from

the humanities; and historical ecology from the sciences (Bowman 2002). The former relies on interpretation of historical documents and images (Ryan *et al.* 1995; Bowman 2002; Butzer and Helgren 2005; Mactaggart *et al.* 2007; Gammage 2008) and the latter, environmental reconstructions using a range of proxies, the most important being dendrochronology (Banks 1982; von Platen *et al.* 2011) and pollen and charcoal in sediments (Swetnam *et al.* 1999; Whitlock and Larsen 2001; Turner and Plater 2004; Higuera *et al.* 2005; Black *et al.* 2007). These approaches are not mutually exclusive, indeed sometimes they motivate and inform each other, and can be effectively merged to provide more robust reconstructions of vegetation cover (Fensham 1989; Batek *et al.* 1999; Benson and Howell 2002; Lunt 2002).

In temperate Australia there is a suite of direct scientific analysis of the transition from Aboriginal to European management (summarised by Dodson and Mooney 2002) but in temperate savanna landscapes there has been a far greater reliance on the analysis and interpretation of historical records (Fensham 1989; Thomas 1994; Griffiths 2002; Lunt 2002; Gammage 2008, 2011). These qualitative studies have been influential on contemporary management practices, especially tree clearing in rural landscapes and bushfire management (Rolls 1981; Benson and Redpath 1997; Jurskis 2000; Mooney *et al.* 2007; Attiwill and Adams 2013). A particularly prominent view is that the amount of landscape burning declined abruptly following colonisation, resulting in a thickening of landscapes that were formerly much more open (Rolls 1981; Jurskis 2000; Franco and Morgan 2007; Gammage 2011). Despite their popular appeal, there has been limited independent verification using robust environmental proxies leading to ongoing debate between scientists and historians about landscape history (Benson and Redpath 1997; Flannery 1997; Jurskis 2000; Bowman 2001).

The Midlands of Tasmania are important in discussions about the nature of landscape changes that followed European settlement. The temperate savannas, which supported high densities of kangaroos and an endemic and now extinct emu, are assumed to have been maintained by frequent landscape burning (Jones 1969; Duncan 1990; Bowman 1998; Jackson 1999; Gammage 2008), a practice that is likely to reach back to the beginning of Aboriginal colonisation some 35 000 years ago (Colhoun and Shimeld 2012; O'Connell and Allen 2015). The open vegetation proved ideal for sheep grazing, so the grassy lowlands of the Midlands were rapidly allocated to free settlers and by 1830, Aboriginal people were completely removed from the area (Fensham 1989; Morgan 1992; Benson and Redpath 1997). This transition resulted in tree clearance, establishment of exotic taxa and the transformation of a focal region of the indigenous economy (Ryan 2012; Prior *et al.* 2013; Romanin *et al.* 2015).

There is a diverse range of evidence to support the hypothesis that Aboriginal people used fire to create or maintain open landscapes in wetter regions of Tasmania (Ellis and Thomas 1988; Jackson 1999; Fletcher and Thomas 2010; Wood and Bowman 2012; Bowman *et al.* 2013). However, there is less evidence to support this hypothesis in the Midlands where there has been a great reliance on the veracity of early colonial paintings that depict vast savanna landscapes with open crown

eucalypts (Duncan 1990; Kirkpatrick 2007; Gammage 2008). The accuracy of these paintings is questionable because they were executed with different motivations. Some artists were employed by the government to create immigration propaganda, which was picturesque and had a strong resemblance to English landscapes, some were trained as surveyors and produced highly accurate landscape representations, still others were artistically trained so used artistic licence to create aesthetically-pleasing scenes (Fensham 1989; Farag-Miller *et al.* 2013). The landscapes of Glover are often referred to as accurate pre-European depictions of the Midlands, his works were criticised by contemporaries for their 'hideous fidelity to nature' (Smith 1960; Fensham 1989). Nonetheless, he portrayed groups of Aboriginal people in landscapes free of European disturbance despite them being expatriated years previously, and independent geographic validation using surveying techniques demonstrates that Glover's landscape features are of low topographic fidelity (Farag-Miller *et al.* 2013). Considering these factors it is reasonable question his artworks' ecological and botanical fidelity as well.

The scientific evaluation of the environmental changes in the Midlands is limited to a dendrochronological study in the dry sclerophyll forest of the eastern tiers (von Platen *et al.* 2011), preliminary palaeoecological examinations of the long-term pollen and charcoal record in a Midlands lagoon (Sigleo and Colhoun 1981), an unpublished thesis looking at the pollen and charcoal record of an additional Midlands lagoon (Jones 2008) and inferences from current demographic structure and open branching habit of old woodland trees (Duncan 1990; Kirkpatrick 2007; Gammage 2008). These studies together suggest that Aboriginal fire was infrequent or low in severity (von Platen *et al.* 2011) and the dominant vegetation was eucalypt savanna with a substantial *Allocasuarina* component (Sigleo and Colhoun 1981; Jones 2008) before European settlement. Immediately after Europeans arrived, fire frequency, as recorded in fire scars, decreased dramatically but increased again in frequency between 1850 and 1980, after 1989 there were few fires recorded (von Platen *et al.* 2011). The single analysis of macro-charcoal in the Midlands showed sparse levels in both the pre- and post-European periods; however, micro-charcoal seems to have been more abundant pre-settlement (Jones 2008). Pictorial evidence used by Duncan (1990) and Gammage (2008) suggest that the elimination of Aboriginal land management resulted in increased density of trees in uncleared fragments, with widely spaced, wide-canopied trees being replaced by narrow crowned, pole saplings and younger trees.

In this study we sampled sediments from seven lagoons and used pollen and charcoal analysis to examine how vegetation and fire regimes at a landscape-level have changed following European colonisation of the temperate savannas of the Midlands of Tasmania. This is the most extensive sampling of this region to date. According to previous research we expect to see a sharp decrease in fire activity post settlement and then a subsequent increase. Trends in the floristic composition of post settlement vegetation are expected to include a mixed signal of increased ruderals and (pasture) grasses and non-native trees, and a loss of native species, particularly herbs and fire sensitive woody taxa including *Allocasuarina*.

Materials and methods

Geographic context

Our study locus was the Midlands of Tasmania – a region that is characterised by fertile river valleys and lateritic plains lying between the Central Plateau to the west and the Eastern Tiers to the east (Fensham and Kirkpatrick 1989; Doyle 1993). The region is in a rain shadow (Fig. 1a) and is the driest part of the island with rainfall between 397 and 626 mm annually, evenly distributed throughout the year (Fig. 1b). Average maximum temperatures range between 9 and 11°C in winter and 21 and 24°C in summer. The regional climate is classified as temperate with warm summer according to Köppen-Geiger classification (Peel *et al.* 2007). Frosts can occur during any month and the average number of frost days across the region is between 75 and 150 per year (Bureau of Meteorology 2008).

The original vegetation of the area based on historical reconstructions was a mosaic of lowland grasslands and grassy eucalypt woodland dominated by *Eucalyptus viminalis* Labill., *Eucalyptus pauciflora* Sieber ex Spreng. and *Eucalyptus amygdalina* Labill. with understorey trees such as *Allocasuarina verticillata* (Lam.) L.A.S.Johnson, *Acacia dealbata* Link and *Banksia marginata* Cav. and a tussock grassland dominated by *Poa labillardieri* Steud. and *Themeda triandra* Forssk. (Fig. 1c) (Fensham 1989; Fensham and Kirkpatrick 1989). Approximately 37% of the region remains under natural vegetation, most of which is highly fragmented (Norton and Lacey 2012) due to extensive clearing for pasture and crops (Fig. 1d) that occurred over the last ~200 years of European settlement. Small wetlands with varying levels of salinity occur throughout the region (David and Browne 1950; Buckney and Tyler 1976; Kirkpatrick and Harwood 1983),

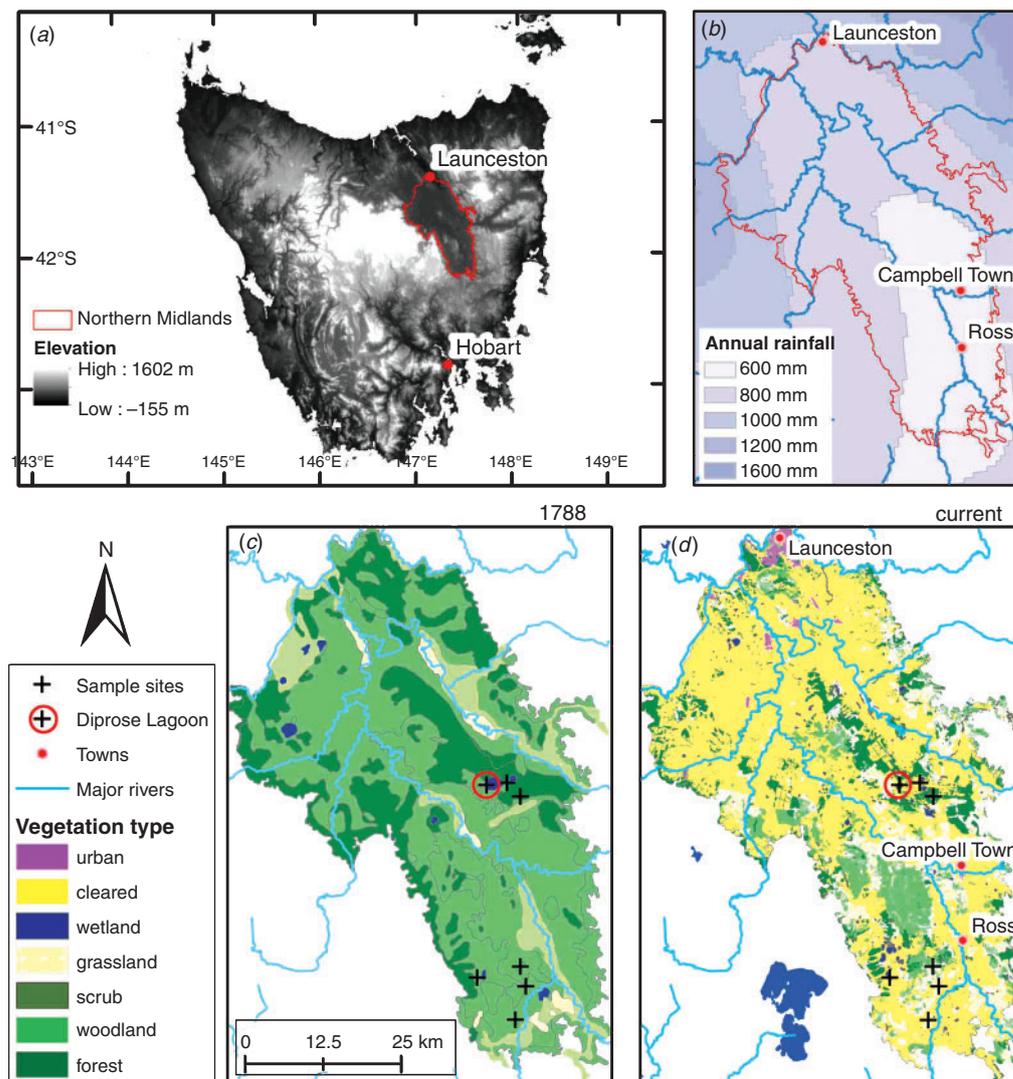


Fig. 1. Geographic context of the study area showing (a) elevation across Tasmania with the study area outlined in red; (b) annual rainfall across the study area which ranges from 600 to 1000 mm annually; (c) a reconstruction of 1788 vegetation patterns (adapted from Fensham 1989) and (d) current vegetation patterns (adapted from TASVEG 2.0; Department of Primary Industries and Water 2009) with locations of sampling sites marked as black crosses in both the 1788 and current vegetation maps. The core from Diprose Lagoon that was ^{210}Pb and ^{14}C dated to obtain calibrated chronology is circled in red.

supporting sedge and rushlands dominated by a suite of genera including *Juncus*, *Baumea*, *Carex*, *Lepidosperma* and *Phragmites* and herblands with ephemeral aquatic plants such as *Myriophyllum* spp. and *Triglochin* spp. where open water is present. The most saline wetlands support salt marsh communities including *Chenopodium* spp. (Kirkpatrick and Glasby 1981).

Sediment sampling

Sediment cores were collected from seven lagoons along a ~40 km long, north–south transect spanning the study area (Fig. 1c, d). The lagoons varied in condition and aquatic vegetation therefore a variety of methods were used to collect sediment samples; sample resolution was necessarily low at one site due to the dryness of the sediments (Table 1). A d-section corer was used where sediments were soft enough for corer penetration. A hammer-driven polycarbonate piston corer was used where sediments were dominated by stiff clays. All cores were wrapped in plastic and stored in PVC tubes. They were kept cool and subsequently subsampled for macro-charcoal and pollen analysis.

Charcoal and pollen analysis

Macro-charcoal particles (>125 µm) are likely to be derived from local fire events (Whitlock and Larsen 2001; Duffin *et al.* 2008). To prepare samples for macro-charcoal analysis, a subsample of 1.25 cm³ of material from each contiguous 0.5 cm increment was extracted. Subsamples with high clay content were deflocculated in Calgon solution for 2–3 days, after which samples were rinsed gently with water. Charcoal subsamples were then treated with bleach for at least 24 h to remove the pigment from organic matter and aid in identifying charcoal (Black *et al.* 2007). Bleached samples were gently washed through a 125 µm sieve to separate macro-charcoal

from organic matter and finer particles. Total macro-charcoal particles were counted under a low power stereo-microscope.

Broad vegetation patterns over time were examined through pollen analysis. Sediment records were sampled at 2 cm intervals; 1.25 cm³ subsamples of these were analysed at Australian National University (ANU) using standard preparation and counting techniques by Bennett and Willis (2001). Pollen identification and nomenclature follows species lists included by Zacharek *et al.* (1997), plant surveys at Tom Gibson Nature Reserve (Parks and Wildlife Service Tasmania 2006) and reference collections held at ANU (<http://apsa.anu.edu.au>, accessed 5 May 2014). *Eucalyptus* and *Allocasuarina* type pollen is assigned based on current vegetation patterns. Terrestrial or dryland pollen counts (including fern spores but excluding aquatic taxa) were expressed as percent pollen of each sample and used in statistical analyses where: (a) taxa that occurred in less than four samples per core or made up less than 1% of the total were excluded from analysis ($n = 17$); (b) all *Rumex* types were treated as one taxon as distinguishing between native and exotic *Rumex* taxa that coexist in Tasmania is problematic; (c) indeterminate pollen grains were also excluded from analysis.

Sediment chronology

Diprose Lagoon was selected for ²¹⁰Pb and ¹⁴C dating at Australian Nuclear Science and Technology Organisation (ANSTO) (Lucas Heights, NSW, Australia). The upper 12 cm of the core was analysed for ²¹⁰Pb activity, and the constant rate of supply (CRS) model was used to develop a chronology for Diprose Lagoon (Oldfield and Appleby 1984). The CRS model assumes a constant flux of unsupported ²¹⁰Pb to the surface sediments through time (Appleby and Oldfield 1978; Binford 1990). This model is suitable for many temperate-zone lakes where ²¹⁰Pb activity has been diluted by recent high sediment accumulation rates (Binford 1990) and is appropriate in this

Table 1. Sampling details of the seven lagoons in the Midlands of Tasmania

The location and landscape setting, sampling methods employed for extracting sediment and their total length of each core, sampling resolution is summarised for each site. The first occurrence of *Pinus* is also noted

Lagoon name	Location	Landscape setting	Sampling method	Length of core	Sampling resolution	<i>Pinus</i> 1st record
Diprose Lagoon	41°48'25.26"S, 147°22'16.26"E	Agricultural land, <i>Eucalyptus amygdalina</i> woodland	Universal core sampler	21.5 cm	2 cm (pollen), 0.5 cm (charcoal)	10 cm
Smiths Lagoon	41°49'22.95"S, 147°26'11.64"E	<i>Eucalyptus amygdalina</i> woodland	Shovel excavation	14 cm	2 cm (pollen), 0.5 cm (charcoal)	10 cm
Near Lagoon	42° 4'11.85"S, 147°26'15.83"E	<i>Themeda</i> and <i>Poa</i> grasslands, <i>Eucalyptus viminalis</i> grassy woodlands and <i>Eucalyptus pauciflora</i> woodland	Auger	36 cm	2 cm (pollen), 2 cm (charcoal)	22 cm
White Lagoon	42° 5'55.92"S, 147°26'55.12"E	<i>Themeda triandra</i> grassland <i>E. viminalis</i> woodland	Universal core sampler	26 cm	2 cm (pollen), 0.5 cm (charcoal)	10 cm
Bells Lagoon	42° 5'10.21"S, 147°21'14.89"E	Agricultural land, native lowland grassland complex, <i>E. viminalis</i> woodland	Universal core sampler	28 cm	2 cm (pollen), 0.5 cm (charcoal)	4 cm
Township Lagoon	42° 8'50.13"S, 147°25'..36"E	Agricultural land, native lowland grassland complex	Universal core sampler	34 cm	2 cm (pollen), 0.5 cm (charcoal)	26 cm
Cleveland Lagoon	41°48'12.71"S, 147°24'38.16"E	Agricultural land, <i>E. amygdalina</i> and <i>E. viminalis</i> woodland	Shovel excavation	21 cm	2 cm (pollen), 0.5 cm (charcoal)	Throughout

landscape characterised by recent vegetation clearance and subsequent erosion (Sigleo and Colhoun 1982). To estimate the ages of the deeper sediments AMS radiocarbon (^{14}C) dating was used. Two samples were analysed, however, only that from 20 cm depth gave an age consistent with the ^{210}Pb chronology, whereas the sample at 15 cm gave an age that is best explained as contaminated with older carbon or otherwise unreliable. Age-depth modelling of the ^{210}Pb and ^{14}C chronology was performed using the CLAM package in R (R Development Core Team 2008; Blaauw 2010); a smoothed spline curve was fitted to the ^{210}Pb and ^{14}C dates. In the remaining six cores the occurrence of *Pinus* spp. was used as an unambiguous, albeit conservative, marker to divide into pre- and post-European periods (Mooney *et al.* 2001). One core (Cleveland Lagoon) was found to have *Pinus* throughout the entire core so was excluded from further analysis.

Data analysis

Changes in macro-charcoal and major terrestrial and aquatic pollen types were investigated for the dated core from Diprose Lagoon through graphical analysis and detrended correspondence analysis (DCA). To determine whether macro-charcoal had changed since the first appearance of *Pinus* spp. (i.e. pre- and post-European periods), all sites except Cleveland were combined, log-transformed, then analysed by a Mann–Whitney U test. Using the percentage pollen data for the six sediment cores, boxplots were generated to examine the distribution of pollen abundance in the pre- and post-European periods for the following ecological groups of taxa: (a) dry sclerophyll forest trees – *Allocasuarina* spp. and *Eucalyptus* spp.; (b) native herbaceous taxa – Poaceae, Asteraceae (Tubuliflorae) and Chenopodiaceae; and (c) exotic ruderal taxa – Brassicaceae, Asteraceae (Liguliflorae) and *Plantago lanceolata*. The difference in pollen percentage between the two periods for these ecological groups was modelled using generalised linear models with a quasibinomial distribution to account for the overdispersed proportion data. All analyses were performed using the R statistical software package (R Development Core Team 2008), ordinations were performed using the vegan package (Oksanen *et al.* 2015).

Results

Diprose Lagoon

The geochronology using ^{210}Pb and ^{14}C of the 22 cm Diprose Lagoon core indicates a continuous and surprisingly linear sediment record over the past ~600 years (Tables 2, 3). The lowest ^{210}Pb measurement at 12 cm depth coincides with European arrival in Tasmania (1803) (Fig. 2a). There are changes in the physical composition of the sediments with the post-European sediments being loamy, whereas the pre-European sediments are clay mixed with organic matter to 18 cm, after which clays are less enriched in organic matter. There is a corresponding strong decline in pollen preservation down the profile with a concentration of 3.2 pollen grains per cm^3 at the lowest depth (21.5 cm).

There were clear changes in floristic composition through the core, with a conspicuous decline in the abundance of the two dominant tree taxa *Eucalyptus* and *Allocasuarina*

throughout the post-European period (Fig. 2b). At the time of settlement, *Eucalyptus* formed ~50% of the pollen assemblage falling to ~10% in the upper (modern) sediments. In the same period *Allocasuarina* declined from 15 to 4% (Fig. 2b). Poaceae (grass) pollen was the most plentiful herbaceous group, being relatively common (7–25%) in the pre-European period, but its abundance dropped immediately after European arrival (Fig. 2c). Since AD1990 Poaceae has become the most abundant (35%) in the terrestrial pollen record. Asteraceae (Tubuliflorae) or ‘native daisy’ pollen also showed a decline following European settlement from being the most abundant herbaceous taxon (25% of the pollen record) in the 14th century (Fig. 2c) declining to 1–5% of the terrestrial pollen in the 20th century. Chenopodiaceae first appeared in the record at around the time of European settlement, and has maintained low levels (~1%) throughout the modern period. Amongst the aquatic pollen, there is a striking transition from *Botryococcus* spp. to *Myriophyllum* spp. at around AD1940 (Fig. 2d). Cyperaceae pollen first appears at AD1870 and increases in abundance towards the surface. *Pinus* spp. also first occurs at around AD1870 reaching peak abundance at AD1960 and declining in modern sediments. Asteraceae (Liguliflorae) pollen is often used as indicator of the European period, but is not diagnostic here as there are native Tasmanian species within this pollen type including the important edible plant, *Microseris lanceolata* ‘yam daisy’, which may have formed part of the diet of Aboriginal people in the region (Gott and Murray 1982). Its presence in both the pre- (AD1630) and post-European sections of the core indicates there were native species in the region that were replaced by exotic taxa (Fig. 2e). A full pollen diagram is

Table 2. ^{210}Pb dating for Diprose Lagoon core from the in the Midlands of Tasmania

Dating was performed by Australian Nuclear Science and Technology Organisation (ANSTO). Depth of sample, level of radioactivity, and calculated age based on a constant rate of supply (CRS) model are supplied

Depth (cm below surface)	Total ^{210}Pb (Bq kg^{-1})	Mass accumulation rates (g cm^{-2} year $^{-1}$)	Calculated CRS ages (years)
0–3	138 ± 6	0.091 ± 0.005	9 ± 3
3–4	139 ± 7	0.053 ± 0.004	26 ± 5
4–5	129 ± 6	0.043 ± 0.004	35 ± 6
5–6	109 ± 5	0.035 ± 0.003	47 ± 7
6–7	82 ± 4	0.028 ± 0.004	66 ± 8
7–8	53 ± 2	0.026 ± 0.005	88 ± 9
9–10	33 ± 2	0.025 ± 0.009	134 ± 12
11–12	23 ± 1	0.014 ± 0.012	192 ± 29

Table 3. ^{14}C AMS dates for Diprose Lagoon core in the Midlands of Tasmania

Depth of sample, $\delta^{13}\text{C}$ of samples and calculated sample ages with 1 σ error are provided

Depth (cm below surface)	$\delta^{13}\text{C}$ per mil	Conventional ^{14}C age	
		^{14}C year before present	1 σ error
15 cm ^A	–30.3	1932	28
20 cm	–35.0	538	22

^ASample excluded from age–depth model due to suspected contamination of sample with older reworked carbon.

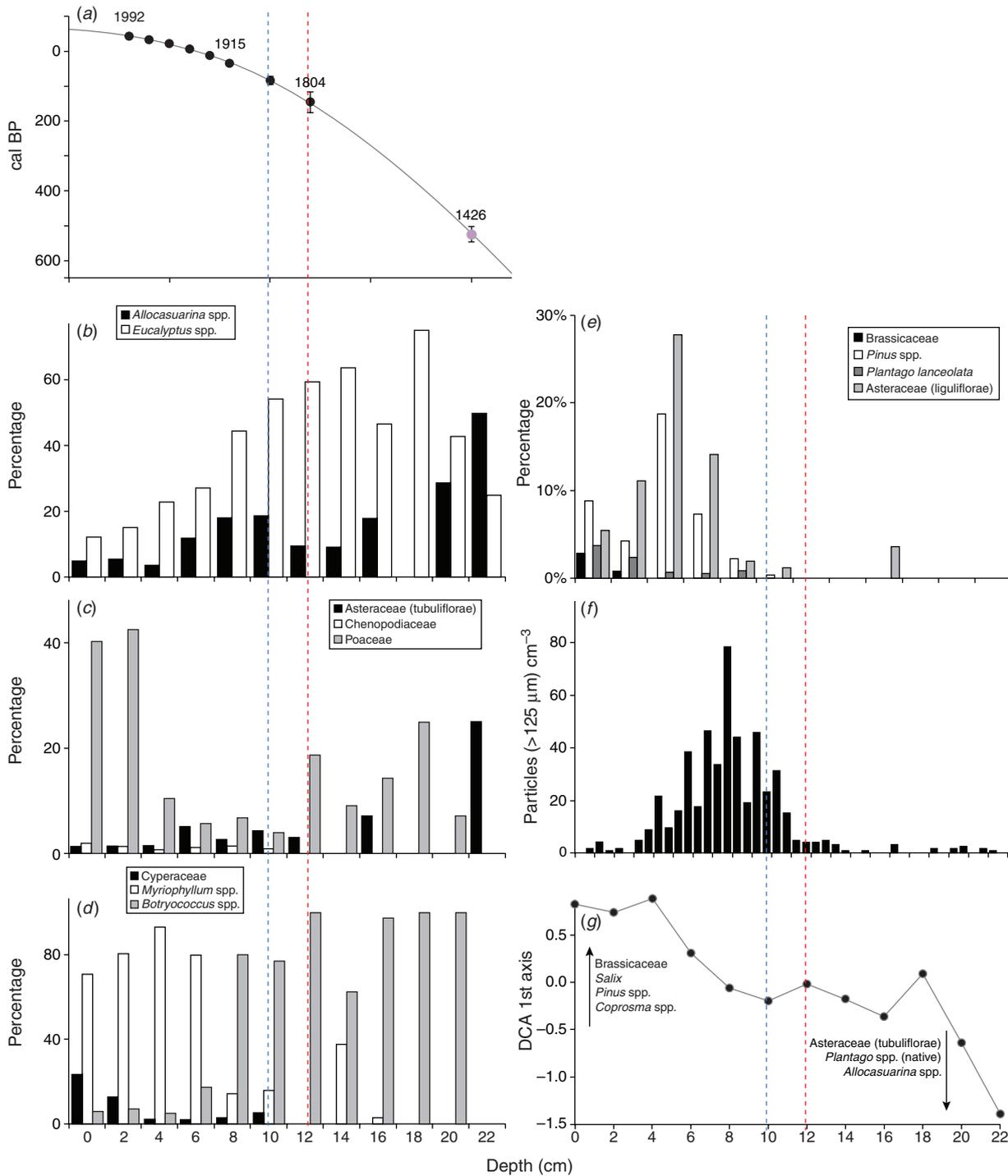


Fig. 2. Variation in pollen and charcoal in the dated core from Diprose Lagoon in the Midlands of Tasmania. (a) An age-depth model was developed using CLAM in R (Blaauw 2010) by fitting a smoothed spline curve to the ²¹⁰Pb (black) and ¹⁴C (coloured purple) dates, estimated ages were converted to calendar years with 1950 as the baseline. The x-axis is depth in cm, with surface sediments at the left. The scale of the y-axis varies in each panel. The blue vertical line indicates the depth at which the first grain of *Pinus* pollen was found, the red vertical line indicates the approximate year that Europeans arrived in Tasmania; (b) percentage of the major dry forest tree taxa pollen, *Allocasuarina* spp. and *Eucalyptus* spp. (based on dryland pollen sum); (c) percentage of native herbaceous groups, Poaceae, Asteraceae (Tubuliflorae) and Chenopodiaceae (based on dryland pollen sum); (d) percentage of aquatic taxa, Cyperaceae, *Myriophyllum* spp. and *Botryococcus* spp. (based on the aquatic pollen sum excluding dryland taxa); (e) percentage of exotic indicator groups including the tree species *Pinus*, and the ruderal herbs, Brassicaceae, *Plantago lanceolata* and Asteraceae (Liguliflorae) (based on dryland pollen sum); (f) contiguous record of macro-charcoal (particles >125 microns with sample resolution of 0.5 cm); (g) the first axis of the DCA plotted against depth of the core, a steep slope of the axis indicates periods of rapid vegetation change. Pollen was analysed at 2 cm resolution.

included in Fig. S1, available as Supplementary Material to this paper.

Charcoal was present throughout the sediment record, though the uppermost sediments, after AD1990, have very low but fairly continuous macro-charcoal deposition. A major peak in macro-charcoal preserved in the sediments was found in the mid-19th and early 20th century (Fig. 2f). After the 1950s charcoal deposition dropped to near pre-European levels. In the pre-European period there is only a small amount of charcoal deposited, with gaps in the record.

The first axis of a DCA ordination of the terrestrial pollen taxa reflects the rate and direction of vegetation change following European settlement (Figs 2g, 3). In the early 20th century there is rapid floristic transition largely driven by the establishment of exotic taxa (Fig. 2e). The taxa that drive this transition are those with the strongest positive DCA scores and include *Coprosma* spp. as well as exotic taxa, Brassicaceae, *Salix* spp., *Pinus* spp. (Fig. 3). This transitional period also corresponds to the peak macro charcoal (Fig. 2f). In the earliest part of the record (AD1320–AD1530) there is also rapid taxonomic turnover that corresponds to the transition from *Allocasuarina* to *Eucalyptus* dominance (Fig. 2b). The native species that comprise the negative portion of the DCA first axis are Asteraceae (Tubuliflorae), *Plantago* spp. (native) and *Allocasuarina* spp. (Fig. 3).

Regional network

Total pollen preservation varied substantially between the wetlands. Township and Cleveland Lagoons had very good

preservation throughout the length of the core. Diprose, White, Near and Smiths Lagoons had excellent pollen preservation in the upper sections of the sediment profile, but much poorer pollen preservation in the deepest sediments, particularly so for Smiths and, as noted previously, Diprose Lagoon. Bells Lagoon had high pollen preservation only in the surface sediment sample, the remainder of this core had poor preservation. Summaries of pollen and charcoal found at the six lagoons not discussed in detail are included in Fig. S2 and a list of all pollen and spore taxa recorded in this analysis is included in Table S1, available as Supplementary Material to this paper.

We used the first incidence of *Pinus* spp. pollen to approximate European settlement (Kodala and MacKillop 1988) in all of the cores except Cleveland Lagoon because it had *Pinus* pollen throughout, and overall pre- and post-European periods were examined. Among the remaining 6 cores *Pinus* constitutes 6% of the total terrestrial pollen with an interquartile range of 0.5–8%. In these cores the first appearance of *Pinus* varied from 4 to 26 cm depth, indicating different rates of sedimentation in the wetlands (Table 1). We used these six cores for statistical contrasts in pollen between the pre (– *Pinus*) and post (+ *Pinus*) European periods. For these cores there was no statistically significant change in the proportion of *Eucalyptus* pollen after the arrival of Europeans across the region ($P=0.484$) (Fig. 4); however, there was a statistically significant decrease in *Allocasuarina* pollen ($P=0.01$) (Fig. 4). In the deepest sections of four cores *Allocasuarina* pollen was at least as common as *Eucalyptus*. There were marked increases in Poaceae pollen abundance after settlement with Asteraceae (Tubuliflorae) and Chenopodiaceae pollen abundance

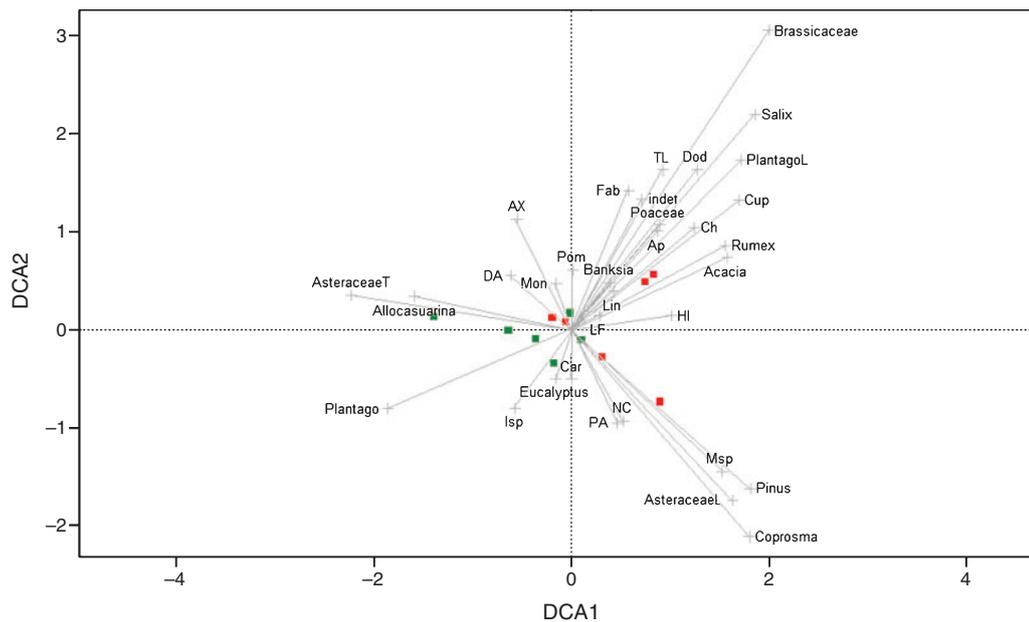


Fig. 3. Detrended correspondence analysis (DCA) of sediment record from Diprose Lagoon. Green squares indicate samples from the pre-European period (as determined by the absence of *Pinus* spp. pollen), red squares indicate samples from the post-European period. All the taxa with a strong influence on the first two axes are indicated where the following abbreviations are used: AP, Apiaceae; AsteraceaeL, Asteraceae (Liguliflorae); AsteraceaeT, Asteraceae (Tubuliflorae); AX, *Amperea xiphoclada*; Car, Caryophyllaceae; Ch, Chenopodiaceae; Cup, Cupressaceae; DA, *Dicksonia Antarctica*; Dod, *Dodonea* spp.; Fab, Fabaceae; HI, *Histiopteris incisae*; Indet, indeterminate pollen grains; Isp, *Isoetes* spp.; Lin, Lindseae LF, *Lagarostrobos franklinii*; Mon, monolet psilate spore; Msp, *Micrantheum* spp.; NC, *Nothofagus cunninghamii*; PA, *Phyllocladus aspleniifolius*; Plantago, *Plantago* spp. (native); PlantagoL, *Plantago lanceolata*; Pom, *Pomaderris apetala*; TL, *Tasmannia lanceolata*.

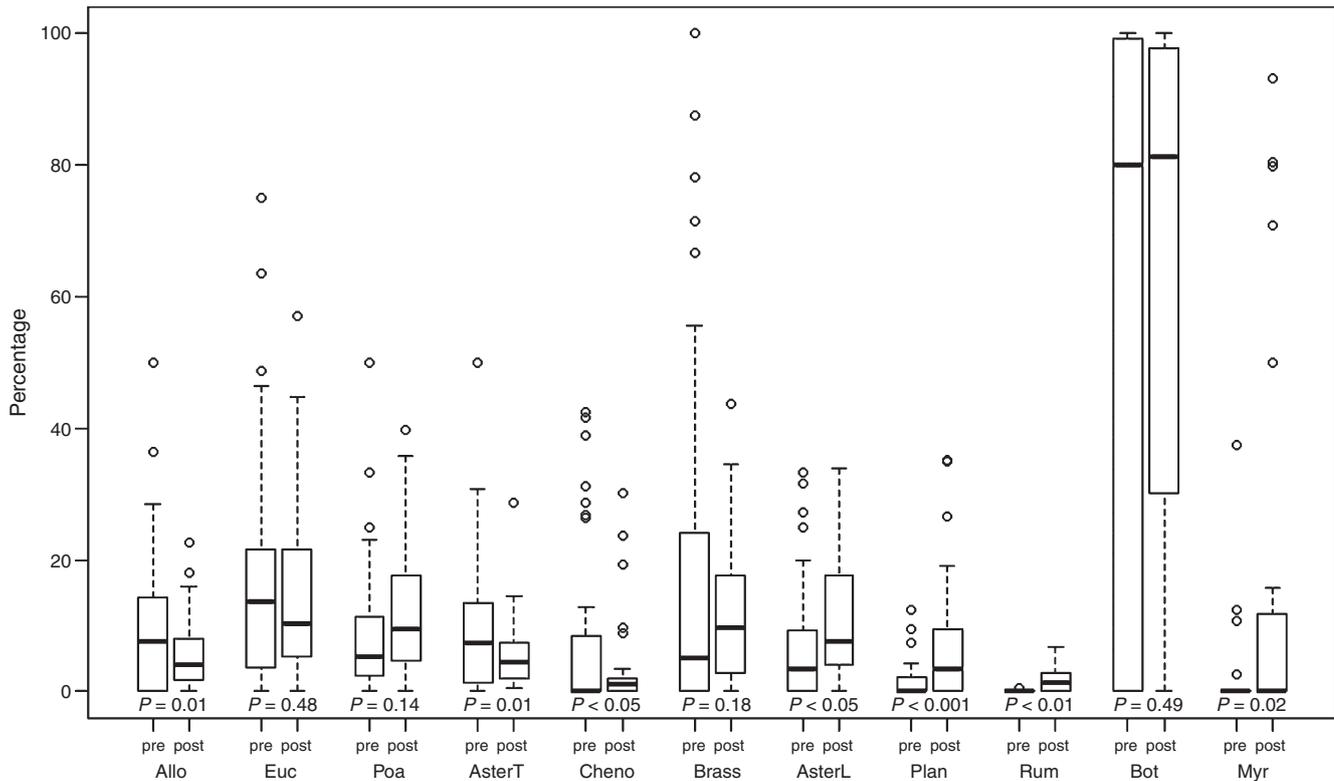


Fig. 4. Differences in the pre- and post-European patterns for pollen data derived from a combined analysis of the 6 sediment cores: showing the dominant dry forest tree taxa, *Allocasuarina* (Allo) and *Eucalyptus* (Euc), native herbaceous taxa, Poaceae (Poa), Asteraceae (Tubuliflorae) (AsterT) and Chenopodiaceae (Cheno), exotic ruderals, Brassicaceae (Brass), Asteraceae (Liguliflorae) (AsterL), *Plantago lanceolata* (Plan) and *Rumex* spp. (Rum) and aquatic taxa, *Botryococcus* spp. (Bot) and *Myriophyllum* spp. (Myr). Pollen values are proportions relative to selected pollen sums (see Fig. 2) and have been converted to percentages for presentation. Probability values based on generalised linear models are shown for each contrast.

significantly decreasing (Fig. 4). Two of the remaining herbaceous taxa examined probably represent a mix of both exotic and native species; native Asteraceae (Liguliflorae) and Brassicaceae species are rare today but they have a strong representation in the early period. Both of these groups have been replaced by exotic ruderal species as indicated by a significant increase in Asteraceae (Liguliflorae) type pollen and an increase in the median value of Brassicaceae pollen in the post-settlement period (Fig. 4). *Plantago lanceolata* is an exclusively exotic species that appeared earlier in the sediment record than the exotic indicator taxa, *Pinus*, at two wetlands (Fig. 4).

The most abundant aquatic taxon was *Botryococcus* spp., it was present at each of the six wetlands examined and made up ~80% of the aquatic record with no significant change in abundance found between the pre- and post-European periods ($P=0.49$). There was a significant increase in *Myriophyllum* spp. ($P=0.02$) after European settlement (Fig. 4).

Minor taxa

Amongst the 6 wetlands, rainforest components, such as *Nothofagus cunninghamii*, *Pomaderris apetala* type and *Phyllocladus aspleniifolius*, were a minor background element (<9%) of total terrestrial pollen. Dry forest species, such as *Acacia* spp., *Banksia marginata* and undifferentiated Fabaceae

species, made up a very low proportion of the total terrestrial pollen, typically individual species comprised less than 6% of the total terrestrial pollen in each core. The highest diversity was found in herbaceous taxa and these were in aggregate more abundant than the previously mentioned groups. *Rumex* was the only taxon to show a statistically significant ($P=0.003$) increase (mean 0.01% to 1.7%) from the pre- to post-European period (Fig. 4). Pteridophyte taxa had constant low background levels ($\leq 3\%$) in all the cores. *Isoetes* was present in all wetlands in both time periods albeit with highly variable levels.

There were only seven aquatic or wetland species represented in the pollen records. None of the minor aquatic species changed in abundance between the two periods. Restionaceae was the only minor wetland family found at all wetlands, it made up 0.3–6% of the aquatic pollen assemblage.

Charcoal

The amount of charcoal preserved at the individual wetlands varied considerably. The amount of macro charcoal preserved in all six sampled wetlands increased from the pre-European (median = 1.6 pieces cm^{-3}) to the post settlement periods (median = 6.8 pieces cm^{-3}) ($U=3215$, $P<0.001$) (Fig. 5).

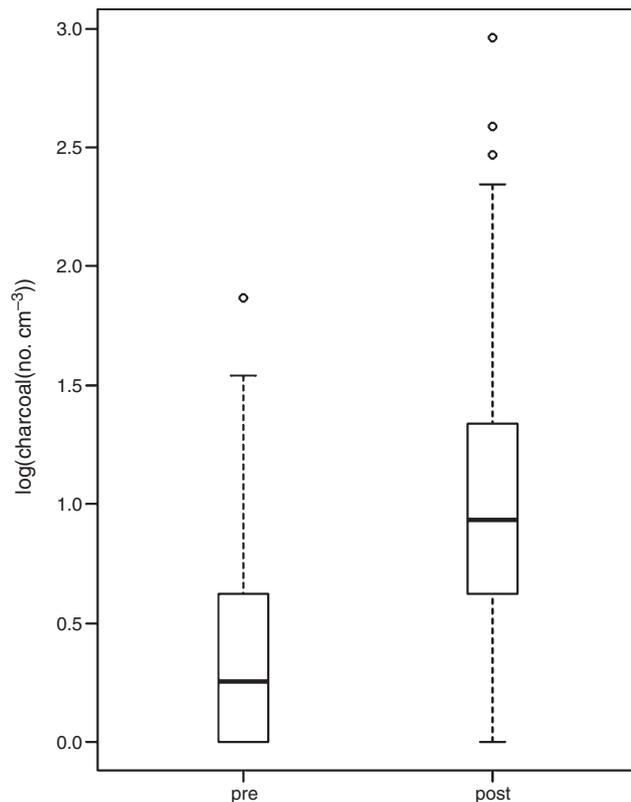


Fig. 5. Boxplots of the differences in the pre- and post-European periods for the macro-charcoal record of six wetlands' sediment cores. Charcoal concentrations of the two periods are log-transformed and differ at the 0.001 level according to a Mann–Whitney test. The pre-European abundance is shown on the left, post-European on the right.

Discussion

Until now there have been few attempts to examine the interplay of vegetation and fire in the dry eastern side of Tasmania, particularly the Midlands (Fensham 1989; Jones 2008; von Platen *et al.* 2011). Most of the historical research in southern Australia has relied upon the accounts of early settlers to evaluate the fire regime of Aboriginal peoples. The paucity of palaeoecological research in this region has been, in part, due to poor pollen preservation and the difficulties in examining sediment records from seasonally dry lagoons because pollen preservation can be inadequate (Thomas 1991) and ^{210}Pb dating can become problematic because drying of sediments may facilitate the downcore movement of ^{210}Pb , which can lead to an underestimate of age at any given depth (Higuera *et al.* 2005). Our approach of using a network of cores enabled us to select a site with good pollen preservation that was suitable for building a chronology, and use other less sensitive sites to draw landscape-level inferences based on statistical analysis of pollen and charcoal in samples amalgamated using a *Pinus* pollen as a marker of European settlement.

Our study demonstrates marked ecological changes in the Tasmanian Midlands following the establishment of a neo-European agricultural landscape. These include a change in woody and herbaceous species abundance associated with

native vegetation clearing and the introduction of exotic pasture species. In addition we found a dramatic increase in fire activity in the terrestrial environment and changed hydrological conditions in wetlands. These findings concur with our research expectations and the findings of previous research (Kershaw *et al.* 1994). In contrast to previous research, however, we found no change in sedimentation rate (Dodson and Mooney 2002). We avoided problems with dating by using *Pinus* as a proxy for the post-settlement period, exotic indicator species have been used to demarcate the arrival of Europeans in both Australia (Kershaw *et al.* 1994; Grayson *et al.* 1998; Kenyon and Rutherford 1999) and America (van Zant *et al.* 1979).

Palaeoecological studies in southern Australia using pollen and charcoal to reconstruct pre-European fire regimes are beginning to reveal the dynamic nature of fire frequency and impact on vegetation during the Holocene although the interpretation of these data is not clear cut (Mooney *et al.* 2001; Fletcher *et al.* 2014). Charcoal peaks in sediments are more likely to reflect high intensity fires (Whitlock and Larsen 2001; Higuera *et al.* 2010). However, the absence of charcoal in a sedimentary record does not necessarily equate to an absence of fire. Low intensity fires produce high levels of incompletely burned particulate matter but this effect is counteracted because these fires are typically small in extent, leaving a small signature in the pollen record (Whitlock and Larsen 2001; Higuera *et al.* 2010). Indeed, Mooney *et al.* (2011) argued that the presence or absence of sedimentary charcoal may be a poor indicator of low intensity fires thought to characterise Aboriginal burning patterns. Studies of traditional Aboriginal fire usage in northern Australia have demonstrated a regime of frequent and patchy fire (Bowman *et al.* 2001, 2004; Bliege Bird *et al.* 2008; Trauernicht *et al.* 2015). They used fire to maintain open grassy landscapes to increase the abundance of game species (Murphy and Bowman 2007; Codding *et al.* 2014) and motivations are assumed to be similar in southern Australia. Dendrochronological evidence shows that dry forests to the east of the study region persisted through increased burning after Europeans arrival, from ~ 0.7 fires per decade under Aboriginal management to 1.7 per decade in the post settlement period (von Platen *et al.* 2011).

Previous studies on mainland south-east Australia have found an increase in charcoal after European settlement (Johnson 2000; Mooney and Dodson 2001; Mooney *et al.* 2001, 2011). Likewise, the charcoal from Diprose Lagoon record showed that there was a sharp increase in charcoal production concurrent with the appearance of *Pinus* in the sediment record. We suggest the source of this charcoal is the combined effects of using fire to clear land and setting geographically large grass fires to stimulate pasture production (Kirkpatrick 2007). In the Diprose core charcoal production in the 1950s declined possibly reflecting a dwindling of tree-clearing and associated burning, and greater use of mechanised agriculture.

The greater abundance of *Allocasuarina* in the period before European settlement suggests that fire regimes were favourable for this species and other relatively fire sensitive species, and that clearing, grazing and an increase in burning by Europeans caused *Allocasuarina* to decline. This inference is supported

by the post-fire regeneration strategies of the two *Allocasuarina* species found in the Midlands. *A. littoralis* is a serotinous obligate seeder that has low fire resistance (Morrison and Renwick 2000; Burley *et al.* 2007), while *A. verticillata* is also serotinous but has a limited capacity to resprout from rootstock (Singh and Geissler 1985; Ladd 1988). Both species regenerate prolifically after fire as they release a heavy rain of seed onto disturbed ground (Ladd 1988) but require at least 5–6 years fire free to begin producing its serotinous seed (Hueneke 1976; Singh and Geissler 1985). A similar pattern of early and rapid decline of *Allocasuarina* has been found in other temperate savannas of southern Australia (Kershaw *et al.* 1994; Mooney and Dodson 2001; Bickford *et al.* 2008; Jones 2008).

We found no significant change in the abundance of *Eucalyptus* pollen following European settlement. This lack of change in *Eucalyptus* was unexpected given the well documented loss of tree cover in the Midlands, which has occurred since European settlement (Fensham and Kirkpatrick 1989; Prior *et al.* 2013; Romanin *et al.* 2015) and may be an artefact of the amalgamation of data from multiple cores. In highly disturbed agricultural areas of New South Wales a similar lack of change in the pollen signature of *Eucalyptus* has been identified with the suggestion that clearing of woodland trees has been compensated by the planting of other species of eucalypts around homesteads or as windbreaks (Kershaw *et al.* 1994). A lack of overall change may also be evidence of thickening of native remnant vegetation after Aboriginal fire management was disrupted (Gammage 2008). Or alternatively, as tree density decreased, flowering, and therefore pollen production, may have increased and left the pollen signature unchanged (Williams *et al.* 2006); the relevance of this to woodland eucalypt species is, however, largely unknown.

These sediment cores provide further circumstantial evidence for a change in the species composition of understorey plants following settlement, including a sharp reduction in abundance of the Aboriginal staple food of southern Australia, *Microseris lanceolata*, or yam daisy (Gott and Murray 1982; Gott 1983, 2005; Clarke 1986). Asteraceae (Liguliflorae) type pollen cannot be identified to species, but except for *M. lanceolata*, *Sonchus megalocarpus* and *Picris angustifolia*, all members in Tasmania are exotic species. *S. megalocarpus* and *P. angustifolia* are only found in coastal regions (<http://www.utas.edu.au/dicotkey/dicotkey/AST/gAsteraceae.htm>, accessed 17 February 2016), so we attribute this pollen type in the pre-European period to *M. lanceolata*. *M. lanceolata* numbers would have declined when active Aboriginal management ceased and introduced sheep began eating them (Gott and Murray 1982). Gott and Murray (1982) point out that the invading European species from the Asteraceae (Liguliflorae) group, such as *Hypochaeris* and *Leontodon*, are adapted to living with sheep and cattle and would have outcompeted *M. lanceolata*.

We found an initial decline then increased abundance of Poaceae in the Midlands following European colonisation. The abundance of Poaceae, in association with *Eucalyptus* and Asteraceae pollen before Europeans arriving supports the notion that eucalypt savanna was the dominant vegetation at the time of colonisation (Ellis and Thomas 1988; Fensham 1989; Kershaw *et al.* 1994). The dramatic loss of native grasslands in the Midlands that has occurred in the 20th century (Gilfedder 1990)

cannot be seen in these sediment records, because native grass species have been replaced by exotic pastures with higher pollen production (Smart *et al.* 1979), especially in the post Second World War period when pasture production was sharply increased (Kirkpatrick 2007). Potentially, quantification of this change from native to exotic grasses could be approximated in future work by measuring the size of Poaceae grains in the sediment record; larger grains may be produced by introduced grass taxa (Kenyon and Rutherford 1999; Bickford *et al.* 2008).

Changes in the composition of aquatic taxa were most apparent at Diprose Lagoon, where a shift in composition from *Botryococcus* spp. to *Myriophyllum* spp. in the mid-20th century was detected. *Botryococcus* is an algal genus which requires standing water (Harle *et al.* 1993) whereas *Myriophyllum* spp. is associated with slow flowing water or the margins of streams. We interpret this transition as reflecting the practise of drainage of wetlands to increase agricultural land, thus producing suitable habitat for *Myriophyllum* to establish in impounded and occasionally flowing artificial drainage channels. Across the Midlands, 34% of wetland area has been drained and a further 23% has been affected by artificial changes in water level (Fensham and Kirkpatrick 1989). In addition to changes in water levels, *Botryococcus* is vulnerable to eutrophication, which may have occurred with increased application of artificial fertilisers and associated increased sheep density in the second half of the 20th century (Kellaway 1989; Kirkpatrick 2007). A shift towards *Myriophyllum* and an overall increase in its abundance throughout the region, is somewhat surprising given its sensitivity to salinity and documented salinity increases in the Midlands (Kirkpatrick and Harwood 1983; Bastick and Walker 2000; Bastick and Lynch 2003). However, some species such as *M. salsugineum*, are known to be tolerant of shallow saline waters (Thomas 1991).

We found no change in sedimentation rate at Diprose Lagoon. This was unexpected because most sediment cores from southern Australia show that a clear increase in sedimentation occurred shortly after the arrival of Europeans in the region (Dodson *et al.* 1994a, 1994b; Mooney and Dodson 2001). Sediment deposition is increased when vegetation cover is removed through fire or tree removal, which allows erosion to occur. An apparent lack of increased sedimentation at Diprose Lagoon could be associated with increased compaction of upper sediments after sheep were introduced and the impact of artificial drainage on catchment hydrology and sedimentation.

Broadly, we support the notion that Aboriginal land management maintained eucalypt savanna and that European disruption of Aboriginal management resulted in changed fire regimes and associated ecological changes, most notably, an increase in fire, a reduction in *Allocasuarina* and increases in exotic taxa. However, we cannot resolve the question of the hypothesised switch from a finer grained to coarse grained spatial pattern of landscape burning that caused the loss of grassland–forest mosaics that lies at the heart of many environmental histories (e.g. Rolls 1981; Jurskis 2000; Gammage 2011). It is possible that integrated studies combining dendrochronology, palynology and charcoal sediment analysis and historical records in the montane grassland–forest mosaics in Tasmania, that are rich in sediment traps and have tree species with annual growth rings, could further

advance this question of the spatio-temporal changes to fire regimes following European disruption of Aboriginal fire management (McWethy *et al.* 2013; Bowman *et al.* 2013; Holz *et al.* 2015).

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