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The fire, human and climate nexus in the Sydney Basin, eastern Australia

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Abstract: It is widely believed that Australian Aborigines utilized fire to manage many landscapes; however, to what extent this use of fire impacted on Australia's ecosystems remains uncertain. The late Pleistocene/Holocene fire history from three sites within the Sydney Basin (Gooches Swamp, Lake Baraba and Kings Waterhole) were compared with archaeological and palaeoclimatic data. The Gooches Swamp record appeared to be most influenced by climate and there was an abrupt increase in fire activity from the mid Holocene perhaps associated with the onset of modern El Niño-dominated conditions. The Kings Waterhole site also displayed an abrupt increase at this time, however there was a marked decrease in charcoal from ~3 ka. Similarly Lake Baraba displayed low levels of charcoal in the late Holocene. At both Kings Waterhole and Lake Baraba archaeological evidence suggests intensified human activity in the late Holocene during this period of lower and less variable charcoal. It is hence possible that Aboriginal people strongly influenced fire activity in some areas of the Sydney Basin during the late Holocene perhaps in response to the increased risk of large intense fires as an ENSO-dominated climate became more prevalent. The fire history within the Sydney Basin varies both temporally and spatially and therefore it is inappropriate to apply a single fire regime to the entire region for landscape management. This work also has implications for future fire incidence associated with climatic variability under an enhanced Greenhouse effect.

Key words: Holocene fire history, climate history, archaeological history, Aborigine impacts, eastern Australia.

Introduction

This study presents contiguous charcoal records from three sites, Gooches Swamp, Lake Baraba and Kings Waterhole, which are all located within the Greater Blue Mountains World Heritage Area in southeastern Australia. The aim of the study was to untangle the influence of climate and people on the late Quaternary fire activity of the region. It is assumed that the three sites have experienced a similar climate throughout this time and therefore any differences in fire activity may be attributed to either the different anthropogenic influences or local biotic or abiotic factors at the various sites. The individual fire and vegetation histories of the three sites have previously been discussed separately (i.e., Black and Mooney, 2006, 2007; Black et al., 2006) however this paper aims to compare the three records and to identify trends across the region.

Jones (1969) suggested that Aboriginal people used ‘fire-stick farming’ to increase or manipulate biotic resources. This has contributed to a popular notion that Aboriginal people controlled a fire regime consisting of frequent, low-intensity fire used with well-defined seasons but over small spatial scales (mosaic or patch burning). There remains much controversy over this generalization and also whether this anthropogenic fire regime impacted on the species composition, structure and distribution of Australia’s vegetation (Bowman, 1998). There are those that believe Australian Aboriginal fire regimes had minimal or no impact on vegetation (e.g., Horton, 1982) while others have suggested that the use of fire has profoundly and irreversibly altered vegetation patterns (e.g., Singh et al., 1981; Flannery, 1994). Clark (1983) and MacPhail (1980) suggested that Aboriginal people may not have altered vegetation patterns but their use of fire was responsible for the continuation of vegetation zones and that they may have affected the rate of vegetation change. Head (1989) argued that Aboriginal people were trying to maintain a balance between the need to fire a landscape for resource manipulation and the need to protect other areas where particular plants grew, such as in rainforests. Head (1989) hence argued that anthropogenic fire practices contributed to the maintenance of a mosaic of vegetation associations.
Palaeoecological studies can provide information on past vegetation and fire activity and have resulted in a better understanding of the prehistory of fire (Wasson and Clark, 1987). In Australia there have been ambiguities associated with interpretations of previous charcoal analyses, leading Bowman (1998) to suggest that palaeoecological studies do not objectively shed light on the issue of Aboriginal use of fire. Despite taphonomic and other concerns the analysis of charcoal ‘remains the best palaeoecological tool for reconstructing fire regimes on millennial time scales’ (Hallett and Walker, 2000: 403).

The prehistory of fire is of relevance to the management of fire in the contemporary environment. As an example, the argument that Aboriginal people applied a low intensity/high frequency fire regime to Australia’s vegetation is often used as a justification for hazard reduction burning (Gill, 1977). Gill (1977) has warned against the adoption of simplistic concepts of Aboriginal use of fire and generalizations over the entire continent. This is demonstrated, as described by Benson and Redpath (1997), by many vegetation types (eg, rainforest, wet sclerophyll forest, alpine shrublands and inland chenopod shrublands) that would now be rare if they had been burnt frequently by Aboriginal people.

The argument for the application of hazard reduction burning in national parks is often more strongly asserted following severe bushfire seasons. Keith (1996) found that frequent widespread burning of the Sydney Sandstone flora could be responsible for local extinctions of plant species and that recolonization spread burning of the Sydney Sandstone flora could be responses to severe bushfire seasons. Keith (1996) found that frequent widespread burning of the Sydney Sandstone flora could be responsible for local extinctions of plant species and that recolonization spread burning of the Sydney Sandstone flora could be responses to severe bushfire seasons.

It is impossible to separate whether charcoal in sedimentary sequences originated from anthropogenic or natural fire events caused, for example, by lightning. One possible method to resolve this is by comparing charcoal records with archaeological data and palaeoclimatic proxies in an attempt to separate human and other influences. Bowman (1998), for example, has highlighted the importance of comparing palaeoecological and archaeological data to better understand fire history. Here the three charcoal records, reflecting local fire activity, will be compared with each other and nearby archaeological information, the latter used as an index of human activity through time.

The Holocene period, from ~11,500 cal. yr BP is generally described as a relatively stable interglacial. Nonetheless there is increasing evidence that the climate of the Holocene contained some variability including abrupt changes, at least in the Northern Hemisphere (eg, Bond and Lotti, 1995; deMenocal et al., 2000; Maasch et al., 2003). In southeastern Australia Kershaw et al. (2002) identified the period of 7–5 ka as the Holocene precipitation peak (the Holocene Climatic Optimum), the period between 4 and 2 ka as a drier and perhaps cooler period, and a return to wetter conditions over the last 2000 years.

One aspect of Holocene climatic variability that has received some attention, and which greatly influences eastern Australia’s climate (Nicholls, 1985), is El Niño-Southern Oscillation (ENSO) events. ENSO is thought to have progressively achieved modern characteristics during the Holocene, although consensus on the timing is yet to emerge (eg, McGlone et al., 1992; Shulmeister and Lees, 1995; Shulmeister, 1999; Rodbell et al., 1999; Clement et al., 2000; Sandweiss et al., 2001; Moy et al., 2002; Riedinger et al., 2002; Gagan et al., 2004).

Westering and Swetnam (2003) suggested that the history of fire in the Western USA contained climatic signals. Furthermore, Haberle and Ledru (2001) suggested that periods of rapid climate change or climatic variability lead to increased fire activity. Increased fire activity has also been variously linked with climatic variability associated with ENSO (eg, Swetnam and Betancourt, 1990; Goldammer, 1999; Haberle and Ledru, 2001; Haberle et al., 2001; Siegert et al., 2001; Kitzberger, 2002; Kershaw et al., 2002).

Haberle and Ledru (2001) identified an alignment in the fire activity from a number of sites in Indonesia and Papua New Guinea, and Central and South America from the mid Holocene and attributed this to the intensification of ENSO variability.

There is a relationship between ENSO and severe fire seasons in Australia, since El Niño events are generally associated with drier and warmer than average conditions, and La Niña events with conditions that are wetter and cooler than average (Lindsey et al., 2004). Edwards (2002) found a particularly strong link between the Southern Oscillation Index and fire season severity in southeastern Australia.

Site description

The sites used in this study are located within the Sydney Basin, on the central east coast of New South Wales, Australia. The Sydney Basin is a geological province of approximately 3.7 million ha consisting of a number of discrete physiographic units that include the Blue Mountains Plateau to the west, the Wollemi-Colo and Hawkesbury Plateau to the north, the Woronora Plateau and Southern Highlands to the south and the central Cumberland Plain (Herbert, 1983) (Figure 1).

The Sydney Basin is dominated by a temperate climate characterized by warm summers and no dry season, although a subhumid climate pertains in the northern parts of the Basin and small areas of Montane climate in the Blue Mountains (National Parks and Wildlife Service (NPWS), 2004). Average annual rainfall is variable across the Basin according to altitu-
dinal changes and the distance from the coast. Shallow skeletal sands are found on the sandstone plateaus and these soils have poor water-holding potential, are very acidic and infertile (Herbert, 1983). Elsewhere soils may be metres deep and enriched by silt and organic matter.

The considerable variation in geology, soils and topography across the Sydney Basin has resulted in one of the most species-diverse botanical divisions in Australia (NPWS, 2004) and includes communities of dry and wet sclerophyllous forests and woodlands, warm temperate rainforests, heath, mangroves and freshwater swamp communities (Benson, 1986, 1992). Heath and woodland are commonly found on the rocky platforms and ridgetops whereas taller open forests occur on the deeper plateau soils and on the lower slopes (Benson, 1986, 1992). Communities of the sandstone plateaus surrounding Sydney are dominated by Angophora, Corymbia and Eucalyptus species and the understorey often consists of members of the Epacridaceae, Fabaceae, Mimosaceae, Proteaceae and Rutaceae families (Benson, 1986, 1992).

The sites utilized herein are all organic deposits associated with freshwater swamps in sandstone-dominated landscapes. In the Sydney Basin freshwater swamp communities are relatively small and isolated and occur as hanging swamps on the sandstone plateaus, as wet depressions where drainage is impeded or on poorly drained Quaternary deposits (Campbell, 1983; Fairley and Moore, 2000). Floristic composition varies locally in relation to soil moisture gradients such that the vegetation on these swamps often consists of complex mosaics of sedges, herbs and shrubs that can tolerate poorly drained habitats.

The locations of the three sites are shown in Figure 1. Gooches Swamp (~33°27’S, 150°16’E, 960 m a.s.l.) is a low relief valley infilled with Quaternary sand and peat swamp in a low headwater valley located on the Newnes Plateau. Kings Waterhole (33°1’S, 150°40’E, 280 m a.s.l.) is a low flow valley infilled with Quaternary sand and peat located within Wollemi National Park, northwest of Sydney. Lake Baraba (34°13’S, 150°13’E, 305 m a.s.l.), is an infilled lake within an entrenched meander at Thirlmere Lakes National Park, in the southwest part of the Sydney Basin. More detailed descriptions of the three sites are given elsewhere (in Black and Mooney, 2006, 2007; Black et al., 2006).

Kings Waterhole and Lake Baraba share similar environmental settings. Average annual rainfall and temperatures, altitude and the swamp and surrounding vegetation communities are broadly similar. Gooches Swamp is located at an elevation of 960 m and hence experiences a slightly different climatic regime to the other sites, with greater variations in temperature throughout the year and a higher average annual rainfall. The surface of Gooches Swamp is dominated by shrubs (eg, Baeckea linifolia, Grevillea acanthifolia subsp. acanthifolia, Epacris paludosa and Leptospermum spp.) and sedges (eg, Restio australis, Baloskion australe, Enopldima minus, Lepydrosia scariosa and Lepidosperma limicola) (Keith and Benson, 1988). The surface vegetation at Lake Baraba and Kings Waterhole is dominated by sedges and rushes (eg, Lepironia articulata, Eleocharis sphacelata, Phylidium lanuginosum, Brasenia schreberi). Lake Baraba is largely infilled but some open water exists at some distance from the site of sampling.

The three sites were inhabited by different Aboriginal language groups in pre-European times. The landscape surrounding Gooches Swamp may have been a place of interaction or a transport corridor for various Aboriginal groups including the Dharug (or Daruk) and Gundungurra people (Stockton and Holland, 1974; Horton, 1994). Aboriginal occupation of the Blue Mountains is often described as spasmodic because of climatic variations and the altitude, rugged topography and limited resources (Stockton, 1970; Stockton and Holland, 1974; Flood, 1980). The archaeological history of the Blue Mountains remains relatively poorly understood with only a limited number of sites studied in detail. The earliest evidence of Aboriginal occupation in the Blue Mountains is dated to ~22.4 ka (Stockton and Holland, 1974).

Brodie (1981) suggested that Aboriginal occupation of the Blue Mountains was sporadic between 14000 and 12000 yr BP followed by a hiatus and then an intensification from the mid to late Holocene. Stockton (2005) suggested that winter and cold conditions generally may have been less of a constraint on occupation than has previously been forwarded. Stockton (2005) also hypothesized that the Blue Mountains may have experienced relatively moister conditions during the glacial period and transition, compared with surrounding regions and may therefore have served as a haven for plants and animals, including people. However Hesse et al. (2003) suggested that vegetation was severely reduced and sand dunes were active in the Upper Blue Mountains during the last glacial maximum therefore making the area inhospitable at this time.

The territory of the Dargimung (also written Darkinjung, Darkinjang and Darkinjung) covered an area south from the Hunter River, including portions of the Macdonald and Colo Rivers and lower Hawkesbury River at Wisemans Ferry (Mathews, 1897; Tindale, 1974; Dhurug and Lower Hawkesbury Historical Society, 1988; Attenbrow, 2003, 2004). Kings Waterhole is situated within this territory. The Dargimung were believed to be mobile hunter-gatherers, who used several base camps as well as many activity locations (eg, sites for hunting and gathering, tool manufacture, etc.) and transit or short-term camps within their country (Attenbrow, 2003, 2004).

The traditional custodians of Lake Baraba are the D’harawal and Gundangarra people. The lakes and wetlands of the Thirlmere Lakes were likely to represent a plentiful supply of food and ethnographic evidence suggests that the Aboriginal people of the region frequently applied fire to the landscape (NPWS, 1995). Attenbrow (2004) has suggested that the establishment of Aboriginal sites in the region increased from ~8 ka, with the habitation rates of these sites generally increasing until the arrival of European people.

**Methods**

Sediment cores were extracted from Gooches Swamp, Lake Baraba and Kings Waterhole using a Russian d-section corer (Jowsey, 1966) to depths of 3.55 m, 6.35 m and 5.55 m, respectively. Cores were photographed and stratigraphies described using a modified version of the Troels-Smith method (Kershaw, 1997). The sedimentary sequences were dated using both conventional radiocarbon dating and Atomic Mass Spectrometry (AMS) at Beta Analytical Inc., Florida and Rafter Radiocarbon Laboratory, New Zealand. Four, five and three radiocarbon dates were acquired for the Gooches Swamp, Lake Baraba and Kings Waterhole sequences, respectively. These dates were calibrated with CALIB v5 (Stuiver et al., 2005) using the IntCal04. 14C (Reimer et al., 2004) and ShCal04.14C (McCormac et al., 2004) data sets.

Macroscopic charcoal was analysed using a modified version of the ‘Oregon sieving method’ (Long et al., 1998) and image analysis (Mooney and Black, 2003). Volumetric subsamples were taken from contiguous 1 cm sections for the Gooches Swamp core, and at contiguous 2.5 cm sections for the Lake Baraba and Kings Waterhole sedimentary sequences. The samples were placed in 8% sodium hypochlorite (bleach) for 24 h to remove the pigment from organic matter and, hence, aid in the identification of charcoal. This was then washed through a 250 μm sieve and
the collected material was photographed in a petri dish using a four megapixel digital camera. The area of charcoal was calculated using image analysis software (Scion Image Beta 4.02 for Windows). Results are expressed as mm² of charcoal per cm³ of sample. The sedimentation rates at Gooches Swamp, King Waterhole and the peat section of Lake Baraba were close to linear and hence the concentration of charcoal was not re-expressed as an influx of charcoal per unit area and time.

The charcoal curves of the three sites were statistically analysed using psimpoll v4.25 (Bennett, 2005). Skewness and kurtosis were tested and a Runs test was used to assess whether the data are showing a trend or just random or normally distributed values with q values >0.05 indicating random data. Three types of correlations (Linear, Spearman’s and Kendall’s) were carried out to test for changes in charcoal representation with age. It has been suggested that a negative correlation (ie, increased charcoal with younger age) could reflect anthropogenic or taphonomic influences. Fourier transformation was used in order to detect peaks in spectral density, indicative of cyclical changes in the charcoal data and to identify cycles that could be associated with known climatic cycles.

The three charcoal records were compared with local archaeological sequences. The Gooches Swamp record was compared with the Capertee 3 archaeological sequence (approximately 35 km from the site) (McCarthy, 1964; Hiscock and Attenbrow, 1998, 2004; Attenbrow, 2004, 2005); the Kings Waterhole record was compared with the Upper Mangrove Creek archaeological record (approximately 30 km from the site) (Attenbrow, 2003, 2004); and the Lake Baraba record was compared with a regional summary of archaeological records compiled by Attenbrow (2004).

Charcoal values for each of the three sites were averaged using a 200 yr moving window and then compared with palaeoclimatic information including the Moy et al. (2002) proxy record of changes in ENSO activity throughout the Holocene; seasonality, based on the difference between January and July insolation at 30°S throughout the Holocene using the data from Berger (1992); and also a general summary of past climates for southeastern Australia (Lees, 1992; Shulmeister, 1999; Kershaw et al., 2002).

Results
Stratigraphy and chronology
The results of radiocarbon dating for Gooches Swamp, Lake Baraba and Kings Waterhole are given in Table 1. The basal dates of the three sedimentary sequences are 14.2 ka (Gooches Swamp), >43 ka (Lake Baraba) and 6.1 ka (Kings Waterhole), respectively. The sediments of Gooches Swamp and Kings Waterhole both displayed a relatively constant rate of accumulation and were composed of humified peat interspersed with clay, charcoal and sand. At Lake Baraba, peat was found above 172 cm, a transition layer of peat and clay from 172 to 410 cm, which became more clayey with depth, and clay below 410 cm. The sedimentation rate of the clays at Lake Baraba is much higher than the other two sites, with the exception of a period of reduced charcoal concentrations from 405 and 275 cm (~8.5–6.5 ka) but increase abruptly to remain high and variable until 200 cm (~5.4 ka). Between 185 and 140 cm (~5.9–5.4 ka) and minor peaks at 170–130 cm (~5.4 ka). Macroscopic charcoal concentrations are very low between 430 and 405 cm (~13.6–8.5 ka), relatively low but variable between 405 and 275 cm (~8.5–6.5 ka) but increase abruptly to remain very high and variable until 200 cm (~5.4 ka). Between 185 and 55 cm (~5.2–1.7 ka) there is a decreasing trend in charcoal concentrations, from relatively high to moderately low and variable throughout this interval. The upper samples (50 to 0 cm, past ~1.5 ka) have very low charcoal concentrations with some samples almost devoid of charcoal. There was much less charcoal found in the clays when compared with the peat sediment. Macroscopic charcoal is present throughout the entire sequence at Kings Waterhole, although the concentrations of charcoal vary considerably. Charcoal is initially low between 555 and 515 cm (~6.1 and 5.7 ka) but then increases dramatically to remain high and variable between 515 and 265 cm (~5.7 ka and 3 ka) with the exception of a period of reduced charcoal deposition between 470 and 430 cm (~5.2 and 4.8 ka). Charcoal decreases rapidly at 265 cm (~3 ka) and remains generally low from this time to the present. Charcoal deposition for the top 80 cm (the past ~1000 yr) is especially low.

Table 1: Radiocarbon dates and calibration for Gooches Swamp, Lake Baraba and Kings Waterhole sediments

<table>
<thead>
<tr>
<th>Site sample depth (cm)</th>
<th>14C date BP with 2σ error</th>
<th>Cal. yr BP* (2σ error)</th>
<th>Lab code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gooches Swamp</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>48–53</td>
<td>1760 ± 60</td>
<td>1419–1811</td>
<td>β-169992</td>
</tr>
<tr>
<td>80–90</td>
<td>2450 ± 60</td>
<td>2333–2708</td>
<td>β-192605</td>
</tr>
<tr>
<td>150–156</td>
<td>4590 ± 130</td>
<td>5322–5912</td>
<td>β-169993</td>
</tr>
<tr>
<td>295–307</td>
<td>10 360 ± 140</td>
<td>11 646–12 737</td>
<td>β-169994</td>
</tr>
<tr>
<td>Lake Baraba</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>147–153</td>
<td>4130 ± 70</td>
<td>4421–4821</td>
<td>β-186144</td>
</tr>
<tr>
<td>275–285</td>
<td>5950 ± 60</td>
<td>6549–6887</td>
<td>β-192607</td>
</tr>
<tr>
<td>347–353</td>
<td>6750 ± 80</td>
<td>7433–7765</td>
<td>β-186145</td>
</tr>
<tr>
<td>464–472</td>
<td>19 411 ± 196</td>
<td>22 541–23 716</td>
<td>NZA-192608</td>
</tr>
<tr>
<td>595–601</td>
<td>&gt;43 630</td>
<td>N/A</td>
<td>β-192608</td>
</tr>
<tr>
<td>Kings Waterhole</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>147–154</td>
<td>2220 ± 60</td>
<td>2003–2327</td>
<td>β-186146</td>
</tr>
<tr>
<td>348–353</td>
<td>3280 ± 70</td>
<td>3269–3635</td>
<td>β-186147</td>
</tr>
<tr>
<td>547–553</td>
<td>5560 ± 90</td>
<td>6014–6491</td>
<td>β-186148</td>
</tr>
</tbody>
</table>

Calibration results from CALIB v5 (Stuiver et al. 2005). The midpoint of the entire calibrated year range is used in age–depth model calculations. (Beta Analytical Inc., Florida and Rafter Radiocarbon Laboratory, New Zealand carried out the radiocarbon dating.)

Charcoal analysis
The charcoal records of the three sites are presented in Figure 2. For the purpose of comparison the charcoal record of Lake Baraba has been truncated at 14.2 ka (430 cm) ie, the basal date of Gooches Swamp. At Gooches Swamp macroscopic charcoal is relatively high between 250 and 281 cm (~9.8–11.1 ka), 232 and 244 cm (~9.1–9.6 ka), 97 and 150 cm (~5.7–5.5 ka), 67 and 87 cm (~3.3–3.1 ka) and 0 and 6 cm (the late European period). There are low levels of charcoal between 325 and 353 cm (~12.9–14 ka), 287 and 315 cm (~11.3–12.5 ka), 150 and 232 cm (~5.7–9 ka), 87 and 97 cm (~3.1–3.5 ka), and from 40 to 25 cm (~1.1–0.5 ka) and 6–13 cm (early European occupation).

Most of the analysed sediment profile from Lake Baraba has low levels of charcoal, with peaks at 240 (~6 ka), 270 (~6.4 ka) and 400 cm (~8.4 ka), a series of higher peaks at 230–200 cm (~5.9–5.4 ka) and minor peaks at 170–130 cm (~5–4 ka). Macroscopic charcoal concentrations are very low between 430 and 405 cm (~13.6–8.5 ka), relatively low but variable between 405 and 275 cm (~8.5–6.5 ka) but increase abruptly to remain very high and variable until 200 cm (~5.4 ka). Between 185 and 55 cm (~5.2–1.7 ka) there is a decreasing trend in charcoal concentrations, from relatively high to moderately low and variable throughout this interval. The upper samples (50 to 0 cm, past ~1.5 ka) have very low charcoal concentrations with some samples almost devoid of charcoal. There was much less charcoal found in the clays when compared with the peat sediment.

Macroscopic charcoal is present throughout the entire sequence at Kings Waterhole, although the concentrations of charcoal vary considerably. Charcoal is initially low between 555 and 515 cm (~6.1 and 5.7 ka) but then increases dramatically to remain high and variable between 515 and 265 cm (~5.7 ka and 3 ka) with the exception of a period of reduced charcoal deposition between 470 and 430 cm (~5.2 and 4.8 ka). Charcoal decreases rapidly at 265 cm (~3 ka) and remains generally low from this time to the present. Charcoal deposition for the top 80 cm (the past ~1000 yr) is especially low.

Statistical analysis
The results of the skewness, kurtosis and runs test are presented in Table 2. The skewness and kurtosis results of all three sites are positive and significant, indicating a common, non-normal shape or distribution. The positive kurtosis results reflect the ‘peaky’ nature of all three records. The
q-values at all three sites are <0.05, suggesting that the data are not random.

The three correlation co-efficients (ie, Linear, Spearman’s and Kendall’s) for the sites are given in Table 3. Gooches Swamp and Lake Baraba display a negative value for all three correlation co-efficients, suggesting increasing levels of charcoal with younger age. Gooches Swamp is the only site that shows a significant trend.

A number of significant cycles are identified from the spectral analyses (Figure 3), however, some caution is necessary as sample resolution and record length can influence the outcome. At Gooches Swamp 41 yr, 1300 yr, 2600 yr and 5900 yr cycles were significant, at Lake Baraba a 73 yr, 3700 yr and 8000 yr cycle were identified and Kings Waterhole had a 54 yr and a 6100 yr significant cycle. The 41, 54 and 71 yr cycles found at Gooches Swamp, Kings Waterhole and Lake Baraba, respectively, are associated with the sampling resolution of the records and hence are not relevant to the analyses.

Similarly the 8000 and the 6100 yr cycles from Lake Baraba and Kings Waterhole are a function of the record length and hence also should be ignored. This means the only significant cycles are the 3700 yr for Lake Baraba, and the 1300 yr and 2600 yr cycles from Gooches Swamp (although the 2600 yr cycle at Gooches Swamp is likely to be linked to the 1300 yr cycle).

**Comparison with archaeological records**

Comparisons of the Gooches Swamp charcoal record with the Capertee 3 archaeological sequence, the Lake Baraba record with the summary of the southern Sydney Basin archaeological data, and the Kings Waterhole with the Upper Mangrove Creek archaeological sequence, are shown in Figures 4, 5 and 6, respectively.

At Gooches Swamp discard rates and average charcoal concentrations are both relatively low between ~9.7 and 6 ka, however average charcoal concentrations were high between ~6 and 3.6 ka whilst discard rates remain low. Artefact concentrations are highest between ~3.6 and 1.7 ka, with the layer ~3–2.3 ka having the highest discard rates. The latter layer corresponds with the very high levels of charcoal. The period ~1.7 ka to present has very low artefact discard rates corresponding with relatively high levels of charcoal accumulation.

Charcoal at Lake Baraba and the number of habitations used in the region both gradually increase from the last glacial maximum (~21–18 ka) to the early Holocene (Figure 6). From ~8 to 7 ka this relationship breaks down, with the number of

![Figure 2](http://hol.sagepub.com) **The results of the macroscopic charcoal analysis for Gooches Swamp, Lake Baraba and Kings Waterhole**

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Statistical analysis results for the three sites’ charcoal data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Mean</td>
</tr>
<tr>
<td>Gooches Swamp</td>
<td>119.3582</td>
</tr>
<tr>
<td>Lake Baraba</td>
<td>46.9872</td>
</tr>
<tr>
<td>Kings Waterhole</td>
<td>44.6821</td>
</tr>
</tbody>
</table>

*Significant at P ≤ 0.05.

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Results of the correlation for the three sites’ charcoal data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Linear correlation</td>
</tr>
<tr>
<td>Gooches Swamp</td>
<td>-0.3442*</td>
</tr>
<tr>
<td>Lake Baraba</td>
<td>-0.0654</td>
</tr>
<tr>
<td>Kings Waterhole</td>
<td>0.3820</td>
</tr>
</tbody>
</table>

*Significant at P ≤ 0.05.
parameters and a climatic summary of southeastern Australia (Figure 7).

The Gooches Swamp charcoal record displays increases in charcoal with the onset of climatic amelioration and the Pleistocene/Holocene transition. There are very low levels of charcoal during the Holocene Climatic Optimum (~9–6 ka) and a dramatic increase in charcoal from the mid Holocene when ENSO frequencies increased. Charcoal remains high and variable from this time to the present under an ENSO-dominated climate. The seasonality increases throughout the Holocene and begins to plateau from the mid Holocene. The Gooches Swamp macroscopic charcoal record follows this general trend, although the changes are much more abrupt.

Kings Waterhole shows an increase in charcoal associated with the onset of an ENSO-dominated climate, however charcoal decreases dramatically at 3 ka whilst ENSO events remained relatively frequent. Similarly there is no obvious relationship with the degree of seasonality and the Kings Waterhole curve.

The increase in charcoal from ~8 ka at Lake Baraba does not seem to be associated with any dramatic change in ENSO frequency (Figure 7). There is a large decrease in charcoal from the mid Holocene at Lake Baraba and this occurs at the same time that ENSO is likely to have began to influence southeastern Australia’s climate. There is no clear association with the seasonality record and the Lake Baraba charcoal curve.

Discussion

There are key differences between the three fire records presented in this study that could, at least on one level, lead to questions regarding the underlying assumptions of this research, namely that charcoal records from sediment sequences are interpretable in terms of palaeo-fire regimes. This assumption has, however, been tested in a diversity of landscapes against historic fires and/or dendrochronology (fire scars), demonstrating that macroscopic charcoal does reflect local fire events (eg, Whitlock and Millspaugh, 1996; and summarized in Whitlock and Larsen, 2001). This suggests that the differences in the three charcoal records across the Sydney Basin reflect real spatial differences in fire.

The fire history of Gooches Swamp appears to be most greatly influenced by climate. The Gooches Swamp record displays an increase in fire activity associated with the Lateglacial/Holocene transition, followed by a decrease associated with the relatively stable Holocene Climatic Optimum. The Gooches Swamp charcoal record also shows an apparent relationship with the increased frequency of ENSO events from the mid Holocene, suggesting a dramatic change in fire activity. During the twentieth century large, intense fires occurred approximately every decade in the Blue Mountains (Cunningham, 1984): based on the similarities in the charcoal curve from the European period and the preceding ~5000 yr we suggest that a similar fire regime was a feature of this landscape since the mid Holocene.

Haberle et al. (2001) constructed a regional cumulative charcoal curve based on ten sites from Indonesia and Papua New Guinea. When this is compared with the Gooches Swamp charcoal record, smoothed using a 41 point running average to match the resolution of Haberle et al.’s (2001) regional charcoal curve, strong similarities are apparent (Figure 8). Haberle et al. (2001) linked the changes in fire activity in this region with the onset of climatic variability during the postglacial transition and with the onset of modern ENSO from the mid to late Holocene.
Figure 4  A comparison of the Gooches Swamp macroscopic charcoal curve with the number of backed and non-backed artefacts from Capertee 3 (Hiscock and Attenbrow, 1998, 2004)

Figure 5  A comparison of the Lake Baraba charcoal curve with a summary of the archaeological data from the southern Sydney Basin compiled by Attenbrow (2004)
Figure 6  A comparison of the Kings Waterhole charcoal curve with the archaeological data from the Upper Mangrove Creek catchment (Attenbrow, 2004)

Figure 7  (a) Seasonality at 30°S based on the difference in insolation between summer and winter (Berger, 1992). (b) The frequency of ENSO events per 100 years based on Moy et al. (2002). (c) The climatic summary of southeastern Australia (Lees, 1992; Shulmeister, 1999; Kershaw et al., 2002). (d) The smoothed Gooches Swamp charcoal record constructed by summing the 200 yr values. (e) The smoothed Kings Waterhole charcoal record constructed by summing the 200 yr values. (f) The smoothed Lake Baraba constructed by summing the 200 yr values.

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The charcoal record from Gooches Swamp also shows some similarity with the seasonality curve (Figure 7), with an increase in fire activity occurring when seasonality increased, although the changes at Gooches Swamp were much more abrupt. Here fire activity may undergo a non-linear change in response to the linear forcing in a manner similar to that proposed for African climate by deMenocal et al. (2000).

Turney et al. (2004) identified a 1490 yr cycle based on spectral analysis of peat humification data from Lynchs Crater in northern Queensland. They associated this cycle with changes in precipitation and long-term changes in ENSO. A similar cyclicity in palaeo-ENSO has been identified in southern Ecuador (Moy et al., 2002) and North America (Wang et al., 2000). The 1300 yr cycle identified in the Gooches Swamp charcoal record may be related to these palaeo-ENSO cycles, further suggesting the climatic control of fire activity at Gooches Swamp.

Based on the comparison of the Capertee 3 archaeological sequence and the Gooches Swamp charcoal curve there does not appear to be any clear association between human activity and fire. However, as previously discussed, the archaeological history of the Blue Mountains is not well understood and it is possible that future archaeological investigations may reveal a stronger relationship. As an example, archaeological evidence from the Sydney region suggests that there were increases in Aboriginal activity from the mid to late Holocene. However, the evidence at hand suggests that the fire history of the Gooches Swamp landscape is responding predominately to climatic controls.

The variability in charcoal at Gooches Swamp since the mid Holocene may also be related to changes in the biotic and abiotic dynamics of the swamp. It is plausible that as the sediment has built up through time the vegetation on the swamp surface has burnt more frequently. This scenario, however, is not supported by the palynology at the site (Black and Mooney, 2006), which demonstrates little vegetation change during the Holocene that would be expected with any seral development of the vegetation. The water-table is likely to have risen concurrently with the accumulation of sediment, since the sediment is accumulating as a result of a rock-fall dammed constriction.

Charcoal values at Lake Baraba are very low during the late Pleistocene/early Holocene and increase dramatically at ~8.5 ka. During this time the number of habitations used in the region by Aboriginal people increase also, hence changes in fire activity could be attributed to humans. Alternatively the increase in charcoal may be related to burning of increased biomass accompanying climatic amelioration.

Abiotic influences are also likely to have affected the charcoal record at Lake Baraba since there is a change in the depositional environment at ~8.5 ka. This change, from a lake to a swamp environment, would occasionally allow fire to consume the vegetation of the swamp surface, thereby explaining why more charcoal was found in the peat sediments compared with the lacustrine clays of Lake Baraba. There is no clear relationship between ENSO frequency and the fire history of Lake Baraba. At this site there is a marked decrease in charcoal in the late Holocene as regional archaeological indices increase dramatically.

Charcoal increases abruptly at 5.7 ka at Kings Waterhole and this is coeval with the increase at Gooches Swamp and hence is also likely to be associated with the onset of ‘modern’ ENSO conditions. Charcoal values remain high and variable from this time until 3 ka and this probably reflects intense fires under an ENSO-dominated climate. At 3 ka charcoal decreases dramatically and remains low for the rest of the record, a trend that mirrors that of Lake Baraba. At Kings Waterhole there is no evidence of any depositional change nor any major vegetation change, as indicated by palynology (Black and Mooney, 2007), to have impacted on the charcoal record. This marked change at
3 ka is, however, temporally associated with changes in the archaeological record of the Upper Mangrove Creek catchment and hence this change in fire activity is likely to be associated with human activity.

The decreased level of charcoal in the late Holocene at both Lake Baraba and Kings Waterhole are hence thought to indicate an anthropogenic change to the fire regime. As to why less charcoal was deposited at these sites under intensified human activity is perhaps best related to a frequent low-intensity fire regime associated with the management of natural resources (eg, Nicholson, 1981; Gott, 2005). Whitlock and Larsen (2001) suggested that fire regimes characterized by frequent and efficient ground fires do not produce much charcoal. Regular low-intensity fires are likely to consume less biomass and hence the production and deposition of charcoal is low, especially if fires within the catchment were relatively small in area.

Previous Australian studies have attributed changes in charcoal to the intensity of fire. Singh et al. (1981: 43) argue that the ‘greater amounts of charcoal particles and the large fluctuations . . . may be consistent with a pattern of intermittent high-intensity fires with considerable accumulation of litter between them’ from Lashmars Lagoon. They also suggest that relatively small amounts of charcoal with lower variability may reflect more frequent and less intense fires but with less accumulation of fuel. Hope (1994) also interprets increases in charcoal as reflecting a change in fire regime from frequent burning to periodic, destructive and intense fires ignited by lightning or the occasional human visitation.

This suggests that during the late Holocene at Lake Baraba and Kings Waterhole Aboriginal people may have intensively managed the landscape. The data also imply that at these sites the swamp surface was not burnt, which is somewhat at odds with previous general descriptions (eg, Gott, 2005) but may reflect the utility of the vegetation found at both sites. Preventing the burning of the swamp surface, by applying high frequency/low intensity to the woodland surrounding the sites, may have protected certain resources, for example food such as turtles and fresh water crustaceans, which survive within these swamps. Perhaps the risk of more intense fires under an ENSO-dominated climate meant that there was an increased need for Aboriginal people to manage fire in some landscapes (eg, Lake Baraba and Kings Waterhole) and the attendant climatic variability also resulted in changes to other management strategies for food procurement.

Conclusion

The three fire records presented here from the Sydney Basin display some key differences, however a number of generalizations can be drawn from the study. The study also has implications for a much wider audience, as the separation of human and natural causes of environmental change is a significant and global endeavour. Similarly, the role of indigenous people in prehistoric landscapes, how fire responds to climate change and variability and the application of palaeoenvironmental information to contemporary environmental issues all have wide applicability.

In southeastern Australia pre-European fire activity is popularly associated with Aboriginal people, however at Gooches Swamp climate appears to be the dominant control on fire activity over the last ~14,200 years. The Gooches Swamp record was most greatly influenced by climate with periods of climatic instability, such the Lateglacial transition and the onset of ENSO-dominated climates from the mid Holocene, associated with higher levels of charcoal. We suggest that the elevated levels of charcoal are due to an increased frequency of intense fires in the catchment and on the woody, wet heath vegetation of the swamp surface. It appears that the Gooches Swamp record is responding to a regional climatic signal resulting in strong similarities with Haberle et al.’s (2001) charcoal curve from the Sahul region. At Gooches Swamp anthropogenic influences are not readily discernable, based on the current archaeological data from the Blue Mountains.

At Kings Waterhole an increase in charcoal occurred at about the same time as at Gooches Swamp, also likely reflecting ENSO-related climatic variability. However, at Kings Waterhole charcoal levels decreased dramatically at the same time as Aboriginal activity intensified in the region. This decrease was also found at Lake Baraba and an altered regime to small scale, less intense but more frequent fires caused by anthropogenic activity is suggested as a cause. Although humans are likely to have manipulated fire, it is probable that this occurred within a framework dictated by the prevailing climate of the time. For example, the risk of more intense fires under a strengthened ENSO-dominated climate may have increased the need for Aboriginal people to closely manage fire, especially in these fire-prone vegetation communities. This creates a complex nexus between climate and humans, resulting in significant variability in fire through time in the region. The charcoal record of Lake Baraba was complicated since there was a change in the depositional environment from a lake to a swamp at ~8.5 ka and this had taphonomic implications for charcoal representation.

The spatial and temporal variations in fire activity within the small geographical region of the Sydney Basin mean that there is not a single pre-European fire management strategy that can be applied across the entire region. The conclusions of this study mirror those of Head (1989: 41) who noted that there is a common assumption that Aborigines ‘had a single ongoing impact’: this erroneous assumption ignores climatic change and human population and cultural changes. Furthermore, the predominance of climate as a control on past fire activity has been described by Kohen (1996) and Kershaw et al. (2002). Kohen (1996: 20–21) concluded ‘perhaps what we are observing in the last few thousand years is the struggle between anthropogenic fires and climate, with climate seeming to come out in front in most situations’. Similarly Kershaw et al. (2002: 19) observed that ‘(the) relative importance of climate and human influence is difficult to assess but evidence . . . suggests that climate was the major driving force’.

This study also highlights the important influences of climate change and variability on fire activity. At Gooches Swamp fire was not necessarily linked with a drier climate but there was an apparent increase in fire activity during periods of climate change. The longer temporal perspective afforded by this study demonstrates that fire appears to be related to ENSO through time, however the nature of this relationship requires further study. With projected rapid anthropogenic-driven climate change in our near future, fire management strategies should be prepared in order to respond to change.

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