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ORIGINAL ARTICLE

Manu P. Black · Scott D. Mooney

Holocene fire history from the Greater Blue Mountains World Heritage Area, New South Wales, Australia: the climate, humans and fire nexus

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Abstract This study presents a reconstruction of the fire activity of the last ~14,200 cal. years BP (before AD 1950) from Gooches Crater Right, located on the Newnes Plateau, approximately 150 km to the west of Sydney (~33°27′S, 150°16′E) within the Blue Mountains National Park. Charcoal analysis and palynology were undertaken with the aim of untangling any inter-relationship between climate, humans and fire. A chronology of the site was provided by radiocarbon dating. The dominant control on fire in this environment during the Holocene appears to be climate. Periods of climate change, identified in previous studies, are associated with higher levels of fire activity. Fire was less ubiquitous between ~9,000 and 6,000 years BP, a period normally described as having a higher effective moisture in south-eastern Australia. The mid-Holocene fluctuations in charcoal may reflect anthropogenic fire, climate forcing or alternatively human responses to any climate change. Coeval changes in palaeoclimatic sequences elsewhere and palynology at the site support a climatic explanation or that Aboriginal people used fire within a climatic framework.

Keywords Fire history · Charcoal · Holocene · Blue Mountains · Australia

Introduction

There are several contentious and poorly understood issues regarding the history of fire in the humid environments of south-eastern Australia (e.g. Bowman 1998). These include questions regarding how Aboriginal people utilised fire in various landscape contexts, whether their use of fire was constant through time, and how strongly anthropogenic activity has influenced fire history when compared to any climatic change. Fire was used by Aboriginal people, according to the popular 'Fire-stick Farming' thesis by Jones (1969), to acquire or to manipulate and thereby increase the availability of resources. The fire regimes of the various Aboriginal people are often depicted as being of high frequency and low intensity and applied across much of the Australian continent. Head (1989, p. 41) noted that there is a common assumption that Aborigines "had a single ongoing impact", potentially ignoring climatic change and population and cultural change.

Although poorly understood, and despite some cautionary caveats (e.g. Gill 1977), assumptions about Aboriginal use of fire prior to European invasion are often used to justify contemporary intensive prescribed burning regimes. Frequent and uniform landscape firing has been found to detrimentally affect biodiversity in Australian terrestrial ecosystems (e.g. Gill and Bradstock 1995) and has been listed as a 'Key Threatening Process' under the New South Wales' *Threatened Species Conservation* Act (1995).

Prior to 1970, Aboriginal occupation, demographics and socio-economics were viewed as static (e.g. see Mulvaney 1971), despite early delineation of late Holocene change (e.g. McCarthy 1964). Lourandos (1980, 1983, 1997) subsequently identified the mid-to-late Holocene as a period of continent wide changes in Aboriginal Australia. From the mid-Holocene, various changes in technology, settlement patterns, social structures and population densities are thought to have intensified occupation (Lourandos, 1983). This change may have altered resource management strategies including the use of fire. It should be noted that Lourandos' (1980, 1983) intensification model has received some criticism (e.g. see Head 1996).

Several researchers have described an increase in archaeological visibility and the use of sites in the late Holocene including in the Sydney Basin (e.g. McCarthy 1964; Stockton 1970; Stockton and Holland 1974;

M. P. Black · S. D. Mooney (✉)
School of Biological, Earth and Environmental Sciences,
University of New South Wales, 2052 Sydney,
NSW, Australia
E-mail: s.mooney@unsw.edu.au
Tel.: +61-2-93858063
Fax: +61-2-93851558

Attenbrow 1982, 2003) and further afield in south-eastern Australia (e.g. Hughes and Lampert 1982; Smith 1982; Beaton 1983; Ross 1985).

The mid-Holocene has also been identified as a period of climatic change in Australasia (Shulmeister 1999) and further afield (Rodbell et al. 1999; deMenocal et al. 2000; Sandweiss et al. 1999). In Australasia, Shulmeister (1999) described a decoupling of the northern (tropical) and southern (temperate) climate systems of Australia at ~5,000 years BP. In southern Australia, this has been described as resulting in increased westerlies, the loss of summer monsoon rainfall and a sharp decline in effective precipitation (Shulmeister 1999).

Increased seasonality in the south-western Pacific since ~5,000 years BP appears to be related to the El Nino-Southern Oscillation (ENSO) (Shulmeister 1999). Rodbell et al. (1999) argued that ENSO progressively achieved modern characteristics by ~5,000 cal. years BP. Sandweiss et al. (2001) described that ENSO events occurred at a low frequency since ~5,800 years BP, followed by an increased frequency since 3,200 years BP. Riedinger et al. (2002) also described an increase in the intensity and frequency of El Niño events since 3,100 cal. years BP.

This study aimed to investigate the post-glacial history of fire at Gooches Crater Right, located in the Blue Mountains to the west of Sydney, using charcoal analysis and palynology. The objective was to examine the timing of any change in fire activity and see if any change could be better related to proposed changes in Aboriginal occupation or climatic controls. This research forms part of a larger study investigating this climate, humans and fire nexus in the Sydney Basin. An overall objective of this and the larger study is to contribute to the management of fire in the contemporary environment by providing a longer temporal perspective of fire activity.

Study area

The Blue Mountains form the elevated western edge of the Sydney Basin, which is a Triassic sandstone-dominated depositional basin in humid south-eastern Australia (Branagan 1979). Gooches Crater is located on the Newnes Plateau, which has an altitude between 900 and 1,200 m above sea level (asl), in the northwest of the upper Blue Mountains. The site (at 33°27′116″S, 150°16′020″E, ~960 m asl), approximately 150 km to the west of Sydney (Fig. 1), is located within the Blue Mountains National Park, which is incorporated into the Greater Blue Mountains World Heritage Area.

Associated with Gooches Crater, and nearby, are several swamps. The work described herein is from Gooches Crater Right (GCR), which is a narrow, elongate swamp in a low slope headwater valley adjacent to Gooches Crater. GCR contains ~6 m of sandy organic sediments and is currently vegetated with a closed wet heath (dominated by *Baeckea*, *Epacris*, *Gleichenia*, *Grevillea*, *Gymnoschoenus*, *Leptospermum*). Eucalypt woodland and open heath surround the site (Benson and Keith 1990). The Blue Mountains are notoriously fire prone with a natural fire season occurring from October to February (Cunningham 1984). The climate of the Newnes Plateau is temperate with an average minimum of −1°C in July and in the hottest month, January, an

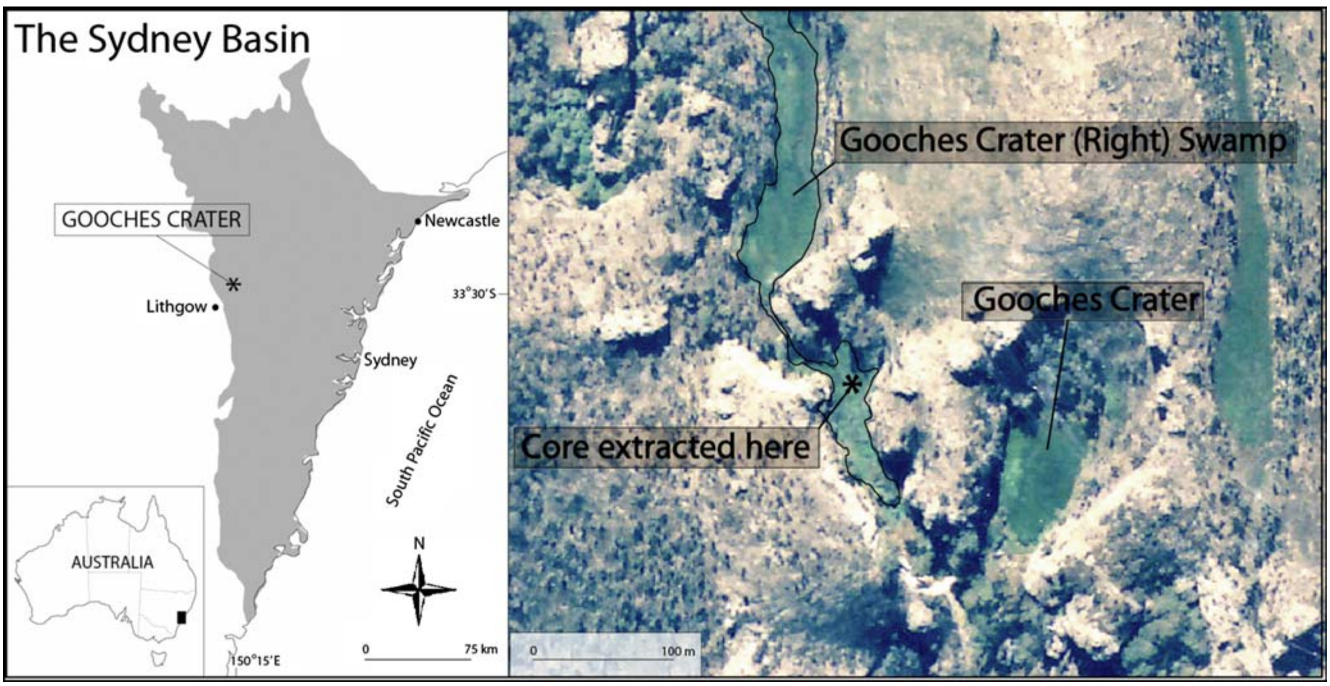

Fig. 1 The location of Gooches Crater Right (GCR). (Photo source: Wallerawang aerial photograph, Run 12, Photograph number 14, Surveyor-General's Department, New South Wales, June 1998)

average maximum of 23.5°C (BoM 2003). The site receives an average annual rainfall of 1,047 mm, which is influenced by a mild orographic effect.

There is conflicting evidence on the timing of the first Aboriginal occupation of the Blue Mountains. Based on archaeological evidence from a site on the Kings Tableland, Stockton and Holland (1974) argued for 22,240 years, however, the consensus suggests human arrival from the late glacial period (Bermingham 1966; I. Johnson, unpublished PhD thesis; Bowdler 1981). Bowdler (1981) suggested that there was sporadic occupation of the Blue Mountains between 14,000 and 12,000 years BP followed by a hiatus and then intensification of occupation associated with the Small Tool Tradition. The Australian Small Tool Tradition saw an enormous expansion of flaking techniques and activity and the addition of smaller implements to the stone tool kit of Aboriginal people. Various authors have dated its introduction to the Blue Mountains at about 4,000 years BP (I. Johnson, unpublished PhD thesis; Bowdler 1981; Stockton 1993); however, Bermingham (1966) had previously suggested abundant Small Tool Tradition artefacts since 5,300 years BP.

Ethnographic sources suggest that Dharug (or Daruk) people were the dominant Aboriginal group to have inhabited the Blue Mountains region (K. Gollan, unpublished data; Kohen 1993). Nonetheless, the Newnes Plateau was probably the western margin of Dharug territory (Kohen 1993) and it may have been a place of interaction or a corridor between the Dharug and people to the west or south (K. Gollan, unpublished data).

The rugged terrain of the Blue Mountains was a constraint for early European exploration, settlement and development (Mackaness 1965). By the time Europeans had found a route over the Blue Mountains in 1813 there were very few Aboriginal people remaining as a result of small pox epidemics and other diseases. Massacres and the destruction of traditional resources resulted in the further demise of Aboriginal populations such that traditional lifestyles had almost completely disappeared from the Blue Mountains region by 1820 (Breckell 1993; Turbet 2001). Currently, national parks, forestry and sand mining dominate land use on the Newnes Plateau.

Materials and methods

A 3.55 m sediment core was extracted from GCR swamp using a Russian d-section corer (Jowsey 1966) in June 2002. A further 2.35 m was extracted in September 2002 giving a sedimentary sequence of 5.9 m. Subsequent dating of this additional core has proven to be problematic, hence only the upper 3.55 m of the sedimentary sequence will be discussed in this paper. The stratigraphy of the core was described using a modification of the Troels–Smith method (Kershaw 1997) and was photographed. Four sections of the core (48–53,

Table 1 The rationale for quantifying the target palynomorphs

Palynomorph	Indicative value[a] (habitats, fire response)
Asteraceae	Generally in dry woodland communities. Tend to be an opportunistic species, responding to opening of the canopy after fire.
Banksia	At GCR, *Banksia* predominantly reflects dry woodland communities (*B. marginata*, *B. spinulosa*) but also as a moist heath shrub (B. ericifolia). Generally considered to be sensitive to fire and frequent fire can result in localised extinctions.
Other Proteaceae	Includes *Hakea* and *Grevillea*, the latter dominated at the site by G. *acanthifolia*, a swamp indicator. *Hakea* occurs in dry heath communities. Generally sensitive to fire.
Casuarinaceae	In the GCR region dominated by *Allocasuarina*, which occur in dry open heath communities. Controversially considered fire sensitive
Chenopodiaceae	In the Sydney region confined to near-coastal environments. At GCR, likely to reflect long-distance transport from arid landscapes to the west.
Epacridaceae	Often occur on swamp margins or in wet heath but some members in woodlands (e.g. *Monotoca*). Likely to be sensitive to fire.
Leptospermum	Leptospermum-type may include *Baeckea*. Predominantly grows on swamps and in wet heath but also in woodland. Sensitive to fire.
Other Myrtaceae	Includes Eucalyptus, the dominant canopy-tree at GCR, and shrubs (*Callistemon*, *Darwinia*, *Kunzea*, *Melaleuca*) common to wetter habitats. Pollen rain probably dominated by Eucalyptus, a dry woodland indicator. Response to fire variable.
Pinus	Introduced genus, roughly indicative of the post-European period. In the GCR region *Pinus radiata* plantations were established in 1919.
Poaceae	Occurs as understorey in woodland communities and swamp margins. Opening of canopy after fire promotes grasses.
Restionaceae	Generally swamp herbs but also in wet heath. Generally tolerant to fire.
Ferns and Mosses	Generally wet heath and swamp habitats but also a component of forest understorey. Pollen spectra dominated by *Glechenia* that regenerates rapidly from rhizomes after fire; favours higher fire frequencies. Also includes *Pteridium* which occurs in drier locations and responds to fire.

[a]Botanical information comes from Fairley and Moore (2000), Benson and Keith (1990) and P. Adam and D. Keith (personal communication)

80–90, 150–156 and 295–307 cm) were submitted for radiocarbon dating.

Macroscopic charcoal, which is thought to represent local or catchment fire events (Whitlock and Millspaugh 1996), was analysed using a modified version of the ‘Oregon sieving method’ (Long et al. 1998) and image analysis. Volumetric sub-samples at 5 cm increments were dispersed for 24 h in 8% sodium hypochlorite (bleach) to remove the pigment from organic matter and hence aid in the identification of charcoal. This material was washed through a 250 μm sieve and the collected material was photographed in a petrii dish using a digital camera (Nikon Coolpix 4500). The area of charcoal was calculated using image analysis software (Scion Image Beta 4.02 for Windows) and charcoal was also counted using a dissecting microscope (×40).

Pollen samples were prepared using standard palynological techniques (Faegri and Iverson 1975). Volumetric samples were taken every 5 cm along the core and exotic pollen (*Alnus*) was added as a ‘spike’. The samples were deflocculated with hot 10% NaOH and then sieved through a 150 μm mesh. Silicates were removed using heavy liquid ($ZnBr_{2(aq.)}$) separation and organic matter with acetolysis. Samples were mounted in silicon oil and 12 pollen types/groups were counted at ×400 magnification until 200 target grains were identified. The pollen counts were expressed as percentages, with all palynomorphs contributing to the pollen sum.

Target palynomorphs were selected for their potential as climatic or fire indicators as described in Table 1. Asteraceae, ferns, Poaceae and Restionaceae were classed as ‘fire tolerant’ whereas Casuarinaceae, Epacridaceae, *Leptospermum* and Proteaceae (including *Banksia*) were classed as ‘fire sensitive’. A fire index was calculated as the ratio between ‘fire tolerant’ and ‘fire sensitive’ palynomorphs.

Pine plantations first occurred in the upper Blue Mountains from 1919 (State Forests NSW, personal communication) and hence the depth of the deepest record of *Pinus* pollen was associated with this date. Full pollen counts were undertaken at five depths, three of which (150,235 and 320 cm) are included in the core under investigation here. Pollen and charcoal diagrams were produced using the Tilia software package (Grimm 1992).

Results

Core stratigraphy and chronology

The analysed sediment core was composed of humified peat interspersed with bands of clay, charcoal, wood and sand. The core description identified very high levels of sand and charcoal between 104 and 132 cm. In the subsequent deeper core, the clay content of the sediment increased gradually below a depth of ~480 cm, such that the base of the core was heavy clay. The ^{14}C dating of the deposit (Table 2) implies a relatively constant rate of accumulation (~0.025 cm $year^{-1}$) in the analysed core. A linear depth–age relationship ($y = 41.218x$–485.98, $R^2 = 0.9931$) is used for all age calculations. Based on this relationship, the analysed core (355 cm) represents ~14,200 cal. years BP. Pollen analysis revealed the first appearance of the exotic taxon *Pinus* at 15 cm.

Charcoal and other analyses

Charcoal, expressed as abundance (no.cm^{-3}) and area (mm^2 cm^{-3}), depict similar trends (Fig. 2) although above ~150 cm charcoal area displays greater variability than the count. There are several limitations associated with the expression of charcoal as abundance, and since there is a very strong correlation between charcoal abundance and charcoal area, only the charcoal area results will be discussed here. Charcoal has not been expressed as an influx (mm^2 cm^{-2} $year^{-1}$) due to the apparent near-linearity of the accumulation rates for the core under consideration here.

The area of macro-charcoal (Fig. 2) is relatively high between 0 and 25 cm (0 to ~550 cal. year BP), 55 and 85 cm (~1,750–3,000 cal. year BP), 95 and 145 cm (~3,400–5,500 cal. year BP), 230 and 245 cm (~9,000–9,600 cal. year BP) and 255 and 290 cm (~10,000–11,450 cal. year BP). There are low levels of charcoal between 160 and 225 cm (˜6,100–8,800 cal. year BP), 290 and 315 cm (~11,400–12,500 cal. year BP) and 325 and 355 cm (~12,900–14,200 cal. year BP). The highest concentration of charcoal was found from the surface sample where the area of charcoal (875 mm^2 cm^{-3}) is almost double that of the next highest peak (437 mm^2 cm^{-3} at 120 cm depth).

Pollen

Myrtaceae pollen (excluding *Leptospermum*) is well represented throughout the profile (Fig. 3), with ferns/mosses, *Leptospermum*, Restionaceae, Casuarinaceae and Poaceae also showing relatively high percentages. The remaining pollen types are poorly represented.

Table 2 Radiocarbon dates from GCR

Depth (cm)	^{14}C date BP	Lab code	$\delta^{13}C$ (‰)[a]	Cal. Yr BP
48–53	1,760 ± 60	*β*-169992	−25	1,700
80–90	2,450 ± 60	*β*-192605	−25	2,470
150–156	4,950 ± 130	*β*-169993	−25	5,560
295–307	10,360 ± 140	*β*-169994	−25	12,190

BP before AD 1950
All calibrations are at the 95% level and are calibrated using INTCAL98 Radiocarbon Age Calibration (Stuiver et al. 1998)
[a]Ratio estimated

There appears to be a moderate level of variability in pollen assemblages between 355 cm (~14,200 cal. years BP) and 200 cm (~7,750 cal. years BP). The variability appears to increase between 200 and 95 cm (~7,750–3,400 cal. years BP). Full pollen counts at 235 and 320 cm (~9,000 and 12,500 cal. years BP) suggest varying environments at GCR from a wet heath with semi-permanent to permanent water to a fern swamp. Between 200 and 155 cm (~7,750–5,900 cal. years BP) the record is dominated by Myrtaceae-type pollen and Casuarinaceae and Asteraceae are also elevated. At ~155 cm (~5,900 cal. years BP), there is a decline in Myrtaceae, Casuarinaceae, *Leptospermum* and Asteraceae representation and a sharp increase in fern and moss spores that continue to dominate the record between 155 and 95 cm (~5,900–3,400 cal. years BP), a period that coincides with high charcoal (Fig. 3).

High charcoal found between 95 and 145 cm (~3,400–5,500 cal. years BP) are matched by high values in the fire index (Fig. 2). Conversely, the low levels of charcoal occurring between 160 and 225 cm (~6,100–8,800 cal. years BP) correspond with a low fire index. There are, however, a number of exceptions to this correlation, notably at 70 cm (~2,400 cal. years BP), 90 cm (~3,200 cal. years BP), 290 cm (~11,500 cal. years BP) and 350 cm (~13,900 cal. years BP) where a high index coincides with low levels of charcoal.

Discussion

The charcoal results from GCR can be interpreted as changing fire activity in response to known climatic events or to changes to Aboriginal society and so the charcoal curve from GCR has been annotated with these influences (Fig. 4). Haberle and David (2004) have particularly emphasised the interplay between changes in climate, culture, resources and habitats, suggesting that a complex interaction between both climate and humans must also be considered.

At GCR, several major trends in fire activity are obvious: this includes fluctuations between ~14,000 and 9,000 cal. years BP; a period of low fire activity from about ~8,900 to 6,100 cal. years BP; a dramatic increase in fire activity from ~5,500 cal. years BP; and a period of increased fire activity between ~1,750 and 3,000 cal.

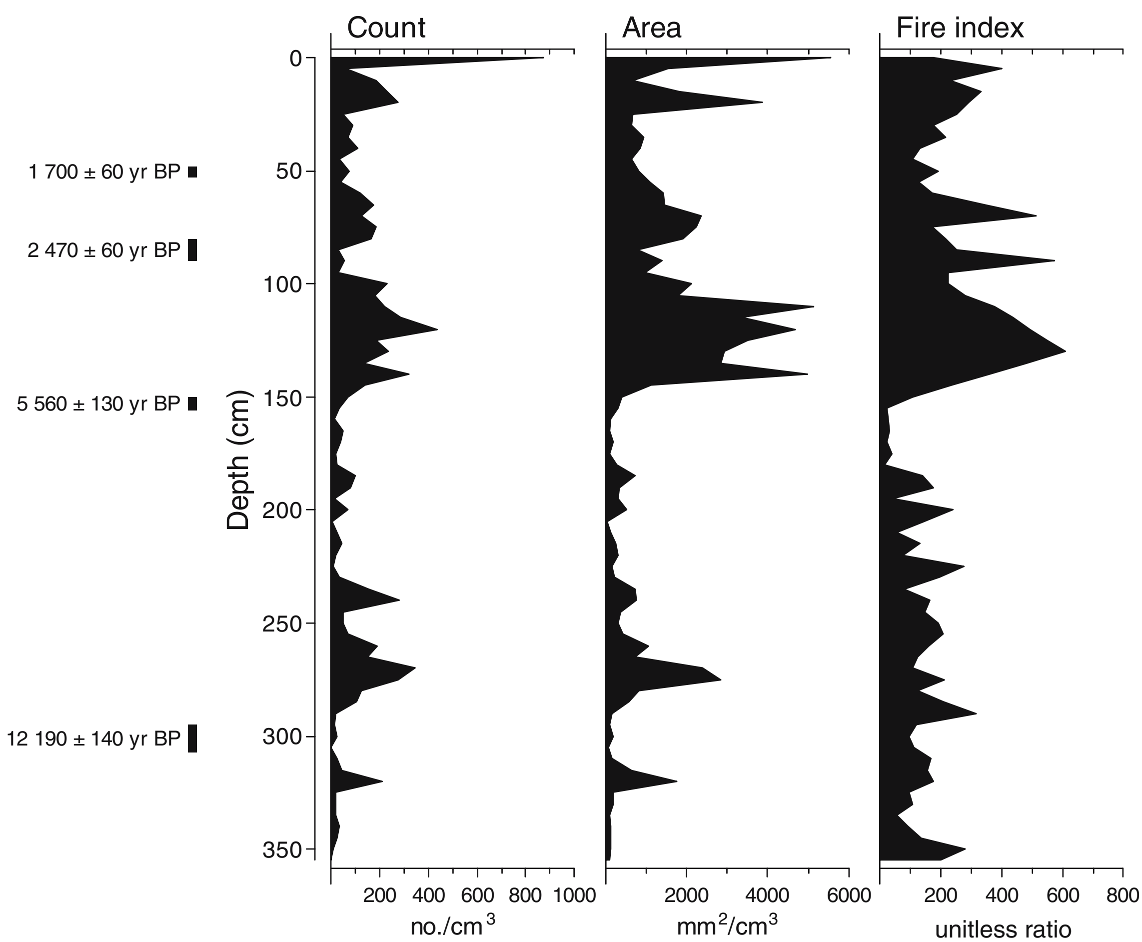

Fig. 2 Charcoal analysis results and the fire index

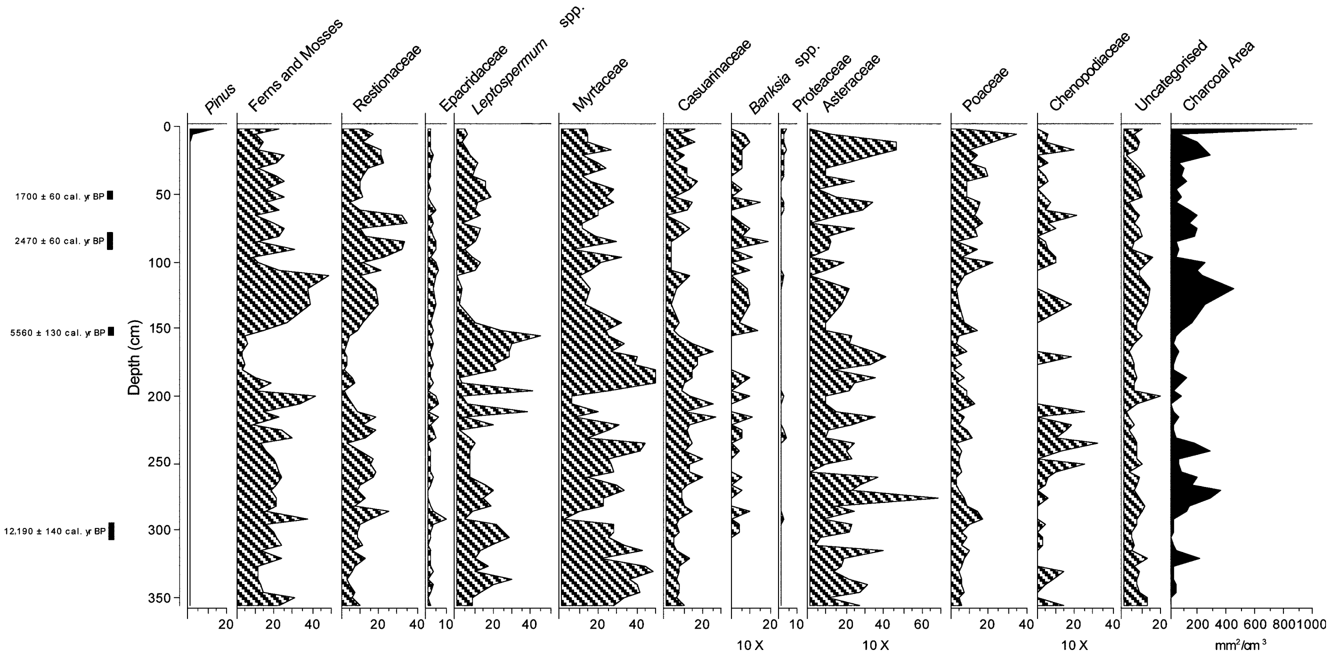

Fig. 3 Palynological results (all units are in percentages, unless otherwise stated)

years BP. The fire activity of the later half of the Holocene appears distinctly different from the earlier Holocene, and this includes unprecedented levels of charcoal in the post-European period.

Using microscopic charcoal and a number of sites located in tropical eastern Indonesia and New Guinea, Haberle et al. (2001) reconstructed the history of fire over the last 20,000 years at a century-scale resolution. In the period of overlap with this study, Haberle et al. (2001) identified identical trends. This included high variability in charcoal for the late-glacial-Holocene transition, low charcoal in the early Holocene and highly variable charcoal values in the later half of the Holocene.

The GCR charcoal record suggests that fire activity was extremely variable between ~14,200 and 9,000 cal. years BP (Fig. 4). This variability includes three peaks centred on ~12,700, ~10,600 and ~9,400 cal. years BP and periods of low fire activity ~14,200–12,900 and ~12,500–11,400 cal. years BP. This trend is reminiscent of palaeoclimatic records of the late glacial-Holocene transition which includes the Antarctic Cold Reversal (~12,900 to ~14,500 years BP) (Blunier et al. 1997) and the Younger Dryas (YD) stadial dated between 12,700 ± 100 and 11,550 ± 70 ice core years in the GRIP ice core (Johnsen et al. 1992), and between 12,940 ± 260 and 11,640 ± 250 ice core years in the GISP2 ice core (Alley et al. 1993).

There has been conflicting evidence concerning the YD event in the Southern Hemisphere. Nonetheless, Goede et al. (1996) found evidence for a YD in oxygen and carbon isotopes ratios of a speleothem from Buchan Cave in Victoria, south-eastern Australia. Haberle et al. (2001) also found a reversal of high charcoal values coeval with the YD and suggested that a relatively cool phase may have altered soil moisture and the vulnerability of the vegetation to fire. Turney et al. (2003) described a cool oscillation that coincided with the ACR, based on palynological and geomorphological research from a number of sites throughout New Zealand. The phase between 14,000 and 11,500 years BP is characterised by an initial cooling period followed by a sustained warming that almost exactly corresponded with the YD event in the Northern Hemisphere (Turney et al. 2003).

The GCR charcoal record reveals a peak in fire activity in the period between the ACR and YD, less fire during the YD, and higher activity at the end of the YD. Haberle et al. (2001) particularly highlighted the importance of the relative stability of climate to fire activity. It is hence possible that the increase in fire activity between ~12,900 and 12,500 cal. years BP was associated with climatic instability during the transition from the ACR phase to the YD phase. Likewise, the increase in charcoal after ~11,400 cal. years BP may reflect the climatic instability associated with the termination of the YD phase.

The time of the ACR corresponds with a slight increase in representation of ferns and mosses and a decreased representation of *Leptospermum* (Fig. 3). Whereas the YD phase saw a slight increase in the representation of fire-sensitive *Leptospermum* and small reductions in the representation of fire-tolerant Asteraceae, Poaceae and Restionaceae, vegetational changes which are consistent with a reduction in fire activity. Despite these observations there are no dramatic changes

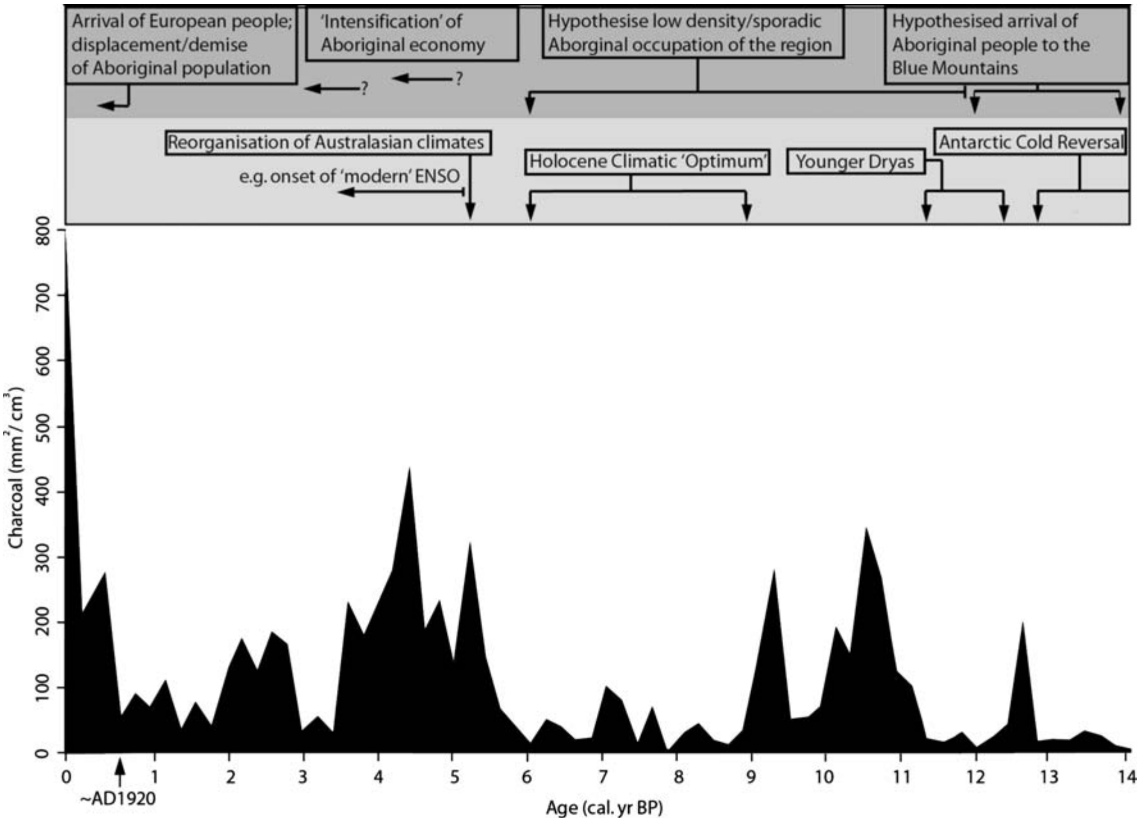

Fig. 4 Annotated charcoal diagram, depicting possible influences on past fire activity at GCR

in the pollen spectra coincidental with the YD. It is possible that the sclerophyllous sandstone vegetation that dominates the Sydney Basin, including around GCR, is relatively insensitive to climatic changes or that the climatic changes associated with the YD and ACR were relatively minor in this setting. Nonetheless, the GCR record suggests a reduction in fire during the YD.

Alternatively, the arrival of Aboriginal people to the Blue Mountains may have affected fire activity (Fig. 4). With climatic amelioration the Blue Mountains was likely to have increasingly become a favourable habitat for people between 12,000 and 10,000 years ago (Stockton 1993). Bowdler (1977) earlier argued that the highlands were not used until after climatic amelioration. Stockton and Holland (1974) suggested that the permanent habitation of the Blue Mountains, especially at higher altitudes, depended on a favourable climate. It is generally assumed that the climate of the Blue Mountains limited occupation of higher altitudes such that they were preferentially used in summer (Stockton 1993).

The variability in charcoal from ~14,200 to 9,200 cal. years BP may, therefore, represent the displacement of Aboriginal people from the upper Blue Mountains as the climate became less suitable for habitation, perhaps during the ACR or YD events, followed by their return as the climatic conditions improved. Haberle and Ledru (2001), in discussing Central and South American fire history, also found elevated charcoal values prior to the Holocene and attributed this to a combined impact of rapid climate change and humans in the landscape. Complex feedback between climate, humans and fire is likely to be a better explanation for the fire activity at GCR between ~14,200 and 9,200 cal. years BP.

The period ~8,800 to 6,100 cal. years BP is characterised by low levels of charcoal coupled with a relatively low variability in the record. In south-eastern Australia Goede et al. (1996) suggested that summer temperatures were depressed by ~2°C between 9,000 and 8,000 years BP and a period of maximum effective precipitation has been identified in southern Australia between about 7,000 and 5,000 years BP (Bowler 1981; Shulmeister 1999). As noted, Haberle et al. (2001) also found low levels of charcoal associated with this period and attributed the low fire activity to climatic stability and reduced seasonality. Notably, Bowdler (1981) suggested a hiatus in the occupation of the Blue Mountains by Aboriginal people in the early-to-mid Holocene.

The fire activity and the fire index at GCR increases dramatically between ~6,000 and 5,000 cal. years BP. The increase in the fire index is largely a result of the increased representation of ferns in the pollen assemblage. *Gleichenia*, the dominant fern found throughout the GCR record, grows on damp to wet ground (Fairley and Moore 2000) so their increased abundance could represent hydrological changes or swamp development associated with a moister climate (D. Keith, personal communication). It is possible that increased effective precipitation could enhance fuel loads, however, this is inconsistent with Shulmeister's (1999) suggestion that there was a sharp decline in effective precipitation in southern Australia at this time. However, Pickett et al. (2004) suggested a wetter climate for some areas including east of the Great Dividing Range.

The increased representation of ferns between ~5,500 and 3,500 cal. years BP may also reflect a response to the higher fire activity as suggested by the high levels of charcoal during this period. *Gleichenia* regenerates rapidly from rhizomes after fire and can form dense thickets (D. Keith, personal communication).

A study by Martin (1994) from coastal Sydney (Kurnell Fen) also revealed an increase in macroscopic charcoal from 5,500 cal. years BP. Martin's (1994) palynological data provided no evidence of climate change at this time and, hence, the increase in charcoal was attributed to Aboriginal activities. This lack of evidence for climate change could, however, reflect the moderating influences of Martin's (1994) coastal location. Further afield, at Lynch's Crater, Kershaw (1983) also found an increase in charcoal between 6,000 and 5,000 years BP.

The increase in charcoal at GCR from ~5,500 cal. years BP is approximately coeval with theorised changes in both climate and Aboriginal occupation. The hypothesised 'intensification' from the mid-Holocene ascribes significant change in Aboriginal Australia to altered social and economic systems (Lourandos 1980, 1983). Changes in Aboriginal technology, resource use, settlement patterns, art, exchange systems and burial have been interpreted as supporting this paradigm (Rowland 1999). Lourandos (1997 p. 299), however, clearly linked intensification with a progressive and continued increase in Aboriginal population levels from mid-Holocene. Earlier, Lourandos (1980) had also argued that increased use of fire might be one result of intensification.

Assuming this model of anthropogenic change is correct and that Aboriginal strategies were associated with fire (e.g. Jones 1969), fire activity should continue to increase from the time of Holocene intensification. In the Blue Mountains region intensification occurred from about 4,000 years BP (e.g. Stockland and Holland 1974; I. Johnson, unpublished PhD thesis; Bowdler 1981; Flood et al. 1987). Bermingham's (1966) earlier date for the Small Tool Tradition assemblage, 5,300 years BP, may reflect the limitations of radiocarbon dating at that time. Overall, these results suggest that the mid-Holocene increase in fire activity at GCR precedes any significant intensification of Aboriginal society by at least 1,500 years. Furthermore, the intensification model depicts a sustained increase in socio-economic activity from the mid-Holocene. The charcoal record at GCR shows a dramatic decline in fire activity centred on 3,500 cal. years BP followed by relatively high activity between ~3,000 and 1,750 cal. years BP. Sustained anthropogenic influence under the 'intensification' model, therefore, cannot be the sole determinant of fire at Gooches Crater. Interestingly, Hiscock and Attenbrow (2004) described a period of relatively high production of Aboriginal backed-artefact between ~1,500 and 3,500 years BP from a site ~35 km north of GCR and Attenbrow (2003) found a dramatic increase in the number of artefacts from about 3,000 years BP from a site ~100 km to the east of GCR.

As an alternative to anthropogenic influences, the changed fire activity at Gooches Crater from ~5,500 cal. years BP may be a response to climate. As described, this timeframe is associated not just with the onset of modern ENSO (Rodbell et al. 1999; Sandweiss et al. 2001), but also with a reorganisation of climates in Australasia (Shulmeister 1999). Riedinger et al. (2002) described considerable millennial-scale variability in El Niño events since the mid-Holocene and notably found few events between 5,000 and 4,000 ^{14}C years BP when charcoal at GCR is high. In fact, Riedinger et al.'s (2002) record of El Niño events, derived from the Galapagos Islands, is often out of phase with fire activity at GCR. Although large fire events in eastern Australia are often popularly linked with El Niño induced droughts, Cunningham (1984) has demonstrated that historic fires in the Blue Mountains normally occur in the first dry fire season following extended periods of above average rainfall.

Shulmeister (1999) argued that after about 5,000 years BP, a relatively sudden change to pressure systems saw the loss of summer monsoon rainfall in southern Australia and the strengthening of the mid-latitude westerlies. This hypothesis can be tested at GCR: Chenopodiaceae in the Sydney Basin, including *Sarcocornia*, *Enchylaena*, *Suaeda* and *Rhagodia*, are confined to coastal locations (Fairley and Moore, 2000) and so their representation at GCR is likely to represent long-distance transport from arid environments to the west of the site. There is a more consistent representation of Chenopods from about the mid-Holocene, although any difference between this period and the early Holocene is subtle (Fig. 3). This avenue of investigation is currently under further consideration.

The high fire activity since the mid-Holocene at GCR, therefore, cannot be simply attributed to either innovations in human society or climatic change. Rather, the higher fire activity may reflect increased climatic variability, as seems likely since ~5,000 years BP, or a complex nexus between climate and human society. For example the D'harawals, the group of Aboriginal people from south-eastern Sydney, recognised three distinctive cycles that affected the weather and "used the indicators of those cycles to predict when to burn the bushland...even the burning of the bushland was not a haphazard exercise" (Bodkin 2004).

The remarkable similarity between Haberle et al.'s (2001) eastern Indonesian and New Guinea sites and the record from GCR, despite the obvious differences in Holocene human occupation and subsistence strongly implies that climate has been the dominant influence over the history of fire. Haberle et al. (2001) suggested influences from the relative position and intensity of the Walker Circulation and the austral summer monsoon. ENSO phenomena are also a key factor (Haberle et al. 2001). Although these potential influences are predominantly tropical systems the Australian climate is strongly influenced by them (e.g. see Shulmeister 1999).

These mid-Holocene climatic anomalies also approximately coincide with the abrupt cessation of the African Humid Period at ~5 500 cal. year BP (deMenocal et al. 2000). deMenocal et al. (2000) suggested that this reorganisation involved teleconnections with the Asian monsoon and linked the cessation of the period with the crossing of a critical threshold in insolation.

Precessional influences on the climate of south-eastern Australia must also be considered in the GCR record of fire activity. Data contained in Berger (1992) indicates that at 30°S December insolation has been increasing over the Holocene whilst June insolation has been decreasing. In the early Holocene Haberle et al. (2001) attributed a lower fire activity to this slightly reduced seasonality and a relatively stable climate in the Malesian region. The history of fire activity at GCR raises the possibility of a non-linear response to the slowly increasing seasonality: again this may reflect direct climatic forcing or responses in human systems to accommodate such changes.

Conclusion

Macphail (1983) suggested that Aboriginal use of fire might either reinforce or oppose trends in vegetation caused by climate change. Here we propose another factor that should be considered: the inter-relationships between climate, humans and fire. It is possible that climate may result in a change in fire activity directly, for example, to ignition of fire via lightning, and at GCR any climatic system that includes dry electrical storms may be important. More probably, climate is likely to influence fire indirectly via vegetation. At GCR, changes in vegetation appear to be associated with fire activity, such that climate influences vegetation through the intermediary of fire. This is not surprising considering the fire-prone sclerophyllous vegetation of the site. At GCR, the vegetation appears to be relatively resilient to climate but is more greatly affected by fire, suggesting that fire history may be a more sensitive index of environmental change than palynology.

This study has highlighted an apparent increase in fire activity during periods of climate change, for example, during the ACR-YD transition and the mid-Holocene. Haberle et al. (2001) came to a similar conclusion in Malesian.

Despite the potential interactions between climate, humans and fire over the last ~14,200 years climate appears to be the dominant control of fire activity at Gooches Crater Right. This is not true, however, in the recent historic past, which has a high fire activity without precedent in the previous ~14,200 years. The suggestion that climate is a dominant control of fire activity in south-eastern Australia is very much at odds with the prevailing paradigm which depicts Aboriginal people as controlling regimes in the pre-European period. This conclusion may also imply that the use of fire for resource manipulation by Aboriginal people in the Sydney Basin has been overstated. Bowman and Brown (1986, p. 166) have previously suggested that 'Fire-stick Farming' had received "too little critical examination", with attendant circular arguments and, hence, it had become a "self-fulfilling prophecy".

This research forms part of a broader project investigating post-glacial palaeoecological records from several sites within the Sydney Basin. The sites have a similar flora, depositional environment and, presumably, have been subject to broadly similar climatic patterns in the past but have been chosen as they were occupied by different Aboriginal groups. Any synchronity in the fire activity at these sites will provide a test of the hypothesis that climate appears to be the dominating factor influencing past fire activity in the Sydney Basin. Alternatively, any differences could imply that fire activity was controlled by people. The results of this broader study will potentially disentangle the nexus between climate, fire and humans.

In terms of management of fire in the contemporary environment, the palaeoenvironmental record at Gooches Crater Right reveals that fire is a significant variable in the environment. There is no single pre-European fire regime that can be recommended as a management target or can be applied: instead several regimes have existed, each tied to the prevailing climate of the time. Furthermore, the Gooches Crater Right study highlights the important influences of climate change including ENSO on fire activity. This suggests that fire activity is likely to become an increasing concern with projected rapid anthropogenic climate change in our near future. How ENSO responds to any anthropogenic climate change is likely to be critical to future fire regimes in south-eastern Australia.

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