Using the Paleorecord to Evaluate Climate and Fire Interactions in Australia

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Abstract

Burning has been a near-continuous feature of the Australian environment but has become progressively more important since the mid-Tertiary, associated with the development of the characteristic sclerophyll vegetation. In the Quaternary, the extent of burning has varied temporally and regionally with glacial-interglacial cyclicity. Burning during glacial periods was reduced in drier areas, presumably because of a critical reduction in fuel availability, but increased in relatively wetter areas where fuel levels were high. On both glacial and Holocene timescales, peaks in charcoal often accompany transitions between fire-insensitive vegetation types, suggesting that burning is facilitated during periods of climate change and environmental instability. This suggestion has been supported by the demonstration of close relationships between fire and El Niño activity. Burning has also increased progressively over the past few hundred thousand years with major accelerations around the time of first human settlement of the continent and with the arrival of Europeans. To provide a firmer base for application of paleofire records to environmental management, there is an urgent need for a spatially more-substantial coverage of high-resolution fire records with good chronological control.

INTRODUCTION

Fire is one of the greatest natural and anthropogenic environmental disturbances in the Australian environment, with vast tracts burned each year. From 1997 to 2003, an annual average of 490,000 km^2 (between 5% and 10%) of the Australian continent was subjected to fire (Russell-Smith 2004), costing the nation more than $77 million annually for firefighting and in lost infrastructure and agricultural productivity (Wahlquist 2006). Bushfires are also Australia's worst natural hazard in terms of loss of life (Chapman 1999), not only resulting in the temporary loss of vegetation but also impacting fauna, landscape stability, and biogeochemical cycles.

The impact can be even greater on a regional basis. For example, in 1997, 244,000 km^2 of Australia's tropical savanna lands were burned, comparable in area to the United Kingdom (Russell-Smith et al. 2003). In the relatively mild fire year of 1992, 5.5% of the total land area of the Northern Territory was burned, consuming an estimated 29.5×10^6 tons of biomass and likely releasing more than 13 Tg of carbon products into the atmosphere (Beringer et al. 1995). In 2003, almost 5% of the total land area of Victoria in southern Australia, including 15% of public lands, were burned in the largest bushfire the state had seen since the Black Friday fire of 1939 (DSE 2003). That same year, a wildfire burned almost 70% of the Australian Capital Territory's farmland and forests, causing the deaths of four people.

Predicted increases of up to 30% in seasonal cumulative fire danger in parts of Australia under predicted climate change (Williams et al. 2001) mean that there is a very real risk that not only the impacts of fires will increase but also that they might exceed the national capacity to deal effectively with the challenge.

Landscape fires have large impacts on regional water, energy, and carbon dioxide exchanges (Görgen et al. 2006), and as a result are likely to drive important feedbacks to the atmosphere and regional climate. Fire can radically alter the surface energy budgets through reduced surface albedo, increased available energy for partitioning into the convective fluxes, and increased substrate heat flux into the soil (Beringer et al. 2003). In addition, the aerodynamic and biological properties of the ecosystem can change, affecting surface-atmosphere coupling and hydrology. Furthermore, different burning regimes can result in either a stable or dynamic change in vegetation composition and structure, which in turn can feed back to affect the atmosphere through changes in land surface properties. Some fire-climate feedbacks are likely to occur through the direct radiative impacts of gaseous and aerosol emissions on the regional and global atmosphere and the indirect role of emitted aerosol particles on cloud convection and precipitation processes.

A variety of indicators of past climate exist that have been or could be used to understand the range of present and future Australian climate variability in the context of fire (Kershaw et al. 2002). Evidence derived from marine and terrestrial sources have, within the past few years, started to provide insights into the role of fire in the Australian paleoenvironment. Nevertheless, it is clear that the full potential of proxy indicators and modeling in the study of fire-vegetation-climate relationships has yet to be realized. This paper reviews the range of methodologies available and the current state of understanding of Australian fire-climate relationships. Important areas of future research are discussed.

METHODS FOR DETECTING FIRE-VEGETATION-CLIMATE RELATIONSHIPS IN THE PAST

There are a number of methods that allow the detection of past fire activity. The most direct are those that measure the incomplete products of combustion, usually from biomass burning, preserved in lake, swamp, and marine sedimentary sequences. Although there is no agreed terminology (Jones et al. 1997), these products can be conveniently divided into the following categories:

1. Fine particulate matter or soot that, owing to its small size, can be transported over long distances in the atmosphere and provide a broad regional or even global picture of biomass burning.
2. Microcharcoal, which is generally categorized as particles between approximately 5 and 100 μm in size and has local to extra-regional dispersal by wind and water.
3. Macrocharcoal, which is categorized as particles more than 100 μm in size that generally have only local dispersal.

Larger charcoal fragments often allow detection of structures that can identify the plants that produced them. Charcoal is extremely resistant to decay and can survive indefinitely in anoxic sediments (i.e., those that are lacking in oxygen). Alternatively, indirect methods that have been used to infer past fires include sustained changes in vegetation, as indicated in pollen sequences; alterations in soil properties, especially magnetic properties; fire scars on trees, and flowering scars on plants where flowering is considered to be triggered by fire. All methods, except those that address archaeological sites, relate directly to vegetation. Potential causes of fire, whether natural or resulting from human activity, have to be inferred.

Hope et al. (2004) described advantages and disadvantages associated with the use of terrestrial and marine paleorecords. The value of terrestrial records is limited by the difficulty of dating beyond the range of radiocarbon (40,000 to 60,000 years; Turney et al. 2001b). Conversely, marine records often have better chronological control, but cores may have a low resolution owing to slow rates of sedimentation and bioturbation. Hope et al. (2004) suggested that paired marine and terrestrial sites may best be used for assessment of patterns of vegetation change, with the marine record often providing valuable chronological control for the terrestrial record. A selection of studies to date is provided below, describing records of past fire from (*a*) examination of micro- and macrocharcoal or of elemental carbon as a measure of the total particulate matter, or from (*b*) the more limited application of fire scars. This selection of Australian studies is a subset of the first global paleofire dataset, designed to provide new insights into the long-term interactions of fire, vegetation, and climate and for the testing of global model simulations (GPD 2006).

Table 1 Characteristics of the sites discussed in the text

Marine site	Longitude	Latitude	Water depth	Record length	Period covered
MD97-2141	121°17′E	8°47′N	3633 m	36 m	0–380 ka
SHI-9014	126°58.289′E	5°46.57′S	3163 m	7.64 m	0–175 ka
G6-4	118°47′E	10°04′S	3510 m	9 m	0–300 ka
MD98-2167	121°35.14′E	13°10.01′S	1981 m	34.26 m	0–480 ka
ODP 820	146°18′E	16°38′S	280 m	68 m	0–250 ka
GC-17	113°30.11′E	22°02.74′S	1093 m	4.5 m	0–100 ka
Terrestrial site	**Longitude**	**Latitude**	**Elevation**	**Record length**	**Period covered**
Lake Euramo	146°38′E	17°10′S	718 m asl	8.4 m	0–23 ka
Lynch's Crater	145°42′E	17°22′S	760 m asl	62 m	0–215 ka
Lake Frome	139°34′E	30°40′S	−2 m asl	3.46 m	0–18 ka
Gooches Crater	150°16′020″E	33°27′116″S	960 m asl	3.55 m	0–14 ka
Lake George	149°25′E	35°5′S	673 m asl	18 m	0–730 ka
Allen's Cave	129°10′E	31°38′S	95 m asl	4.8 m	0–50 ka

Microcharcoal

Microcharcoal particles have been counted, generally in association with pollen, in numerous sedimentary sequences to provide a measure of fire and its impact on timescales covering tens to millions of years. Of particular interest have been records derived from marine cores, especially around the northern perimeter of Australia (ODP Site 820, core GC-17, Lombok Ridge core G6-4, and core SHI-9014; **Table 1**, **Figure 1**) (Kershaw et al. 2002). These records have provided critical information on regional patterns of fire-vegetation-climate relationships from areas where a lack of sedimentary basins on land has inhibited study. However, each has its own pollen and charcoal transport characteristics that need to be understood to determine the nature and impacts of past fire regimes. For example, ODP Site 820 is located on the continental slope of northeast Queensland, and researchers assume that the majority of this sediment was transported by major rivers originating from the center of the humid Australian tropics over the past 250,000 years. Conversely, pollen and charcoal from core GC-17, located near the western coastal extension of the arid interior of Australia, were likely derived mainly by wind transport from the adjacent land.

The interpretation of microcharcoal is uncertain in swamp and lake as well as marine sediments. Furthermore, the unpredictable temporal and spatial characteristics of fire make it difficult to establish close relationships between fire activity, charcoal production, and deposition (e.g., Clark & Patterson 1997). Although there is a generally accepted positive relationship between fire activity and charcoal production, it is difficult to quantify. The relationship between charcoal abundance and vegetation change is also unclear, with fire peaks preceding vegetation change in some records and following vegetation change in other records (Kershaw et al. 2006).

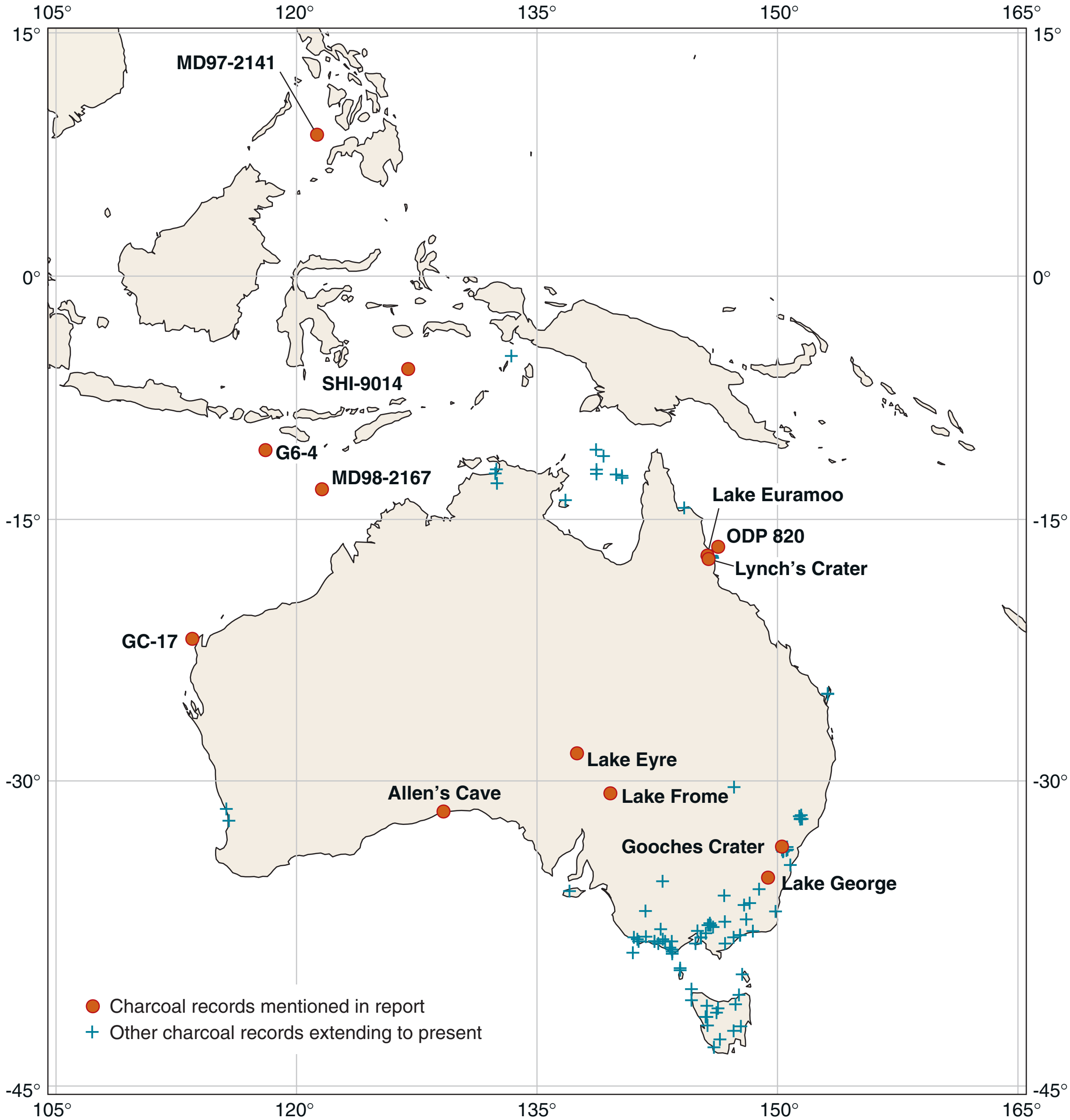

Figure 1

Late Quaternary sediment-based records of past burning within the Australian region. Named sites are those discussed in the text. Dots indicate records covering at least one glacial-interglacial cycle, whereas crosses indicate shorter records, mainly restricted to the Holocene.

Macrocharcoal

Macrocharcoal, because of its relatively restricted dispersal, has greater potential to provide detailed information on fire regimes from defined areas, vegetation types, and specific plant types. Unlike microcharcoal it is also not subjected to the same potential problem of breakage and consequent distortion of the fire signal during chemical preparation. There has been a great deal of background research on patterns of dispersal and deposition of macrocharcoal in recent years, mainly in North America. Charcoal can provide an indication of the frequency of burning within specific communities, but factors such as the timing of fires in relation to the nature of subsequent rainfall can influence the signature (Clark et al. 1998, Lynch et al. 2004, Ohlson & Tryterud 2000, Whitlock & Millspaugh 1996).

In Australia, sedimentary macrofossil research has focused on the mid-east coast (e.g., Mooney et al. 2001, Mooney & Black 2003, Mooney & Radford 2001, Black & Mooney 2006, Black et al. 2006, Mooney & Maltby 2006) and the humid tropics of northeast Queensland (e.g., Haberle 2005). Some of these studies provide direct comparisons of the results of microcharcoal and macrocharcoal from the same records. A record from the Blue Mountains covering the past 14,000 years (Black & Mooney 2006) revealed peaks in fire activity at major transitions in the late glacial period and during the past 5500 years (with the largest peak associated with European arrival), consistent with microfossil records from other parts of Australia. They concluded that with the exception of the peak associated with European arrival, climate exerted the major control over fire activity.

Localized fire histories have been derived from the identification and dating of charcoal preserved in soil profiles. These have been directed toward understanding the dynamics of wetter forest systems, but they may also provide valuable data on climate-fire relationships and on abrupt events. Analysis of charcoal fragments from the humid tropic highlands of northeast Queensland has generally supported a microfossil and pollen record from Lynch's Crater, demonstrating that sclerophyll vegetation, maintained by burning, replaced rainforest during the later part of the late Quaternary and into the early Holocene in association with fire (Hopkins et al. 1993). These studies appear to demonstrate that this was a broad regional event. Soil charcoal from a wet sclerophyll forest site, adjacent to temperate rainforest in central Victoria (southeast Australia) has revealed ages that are either older than 40,000 or younger than 2000 years (McLeod 2004). This pattern probably relates to either the vegetation type or degree of stability in the environment, both of which have climatic implications. This pattern of burning contrasts with that derived from a microfossil charcoal in the Central Highlands (McKenzie 1997) and is subject to further investigation.

Elemental Carbon

Elemental carbon incorporates all burned organic material, including soot as well as micro- and macrosized particles of charcoal that are chemically isolated from sediment samples (Smith et al. 1973, Bird & Gröcke 1997). It has the potential to provide a comprehensive measure of all the products of biomass burning. The technique is also valuable because the isotopic composition of the carbon can be determined, thereby providing information on the broad vegetation groups (i.e., trees and grasses) from which the carbon was derived (e.g., Cachier et al. 1989). The Australian interior is dominated by plants with C_3 ($\delta^{13}C = -26.5$ per mil) and C_4 ($\delta^{13}C = -12.5$ per mil) photosynthetic pathways; in Australia, the photosynthetic pathway depends primarily on the most effective season of rainfall.

OREC: oxidation-resistant elemental carbon

This technique has only been applied to Australian records in a few instances, producing mixed results. At Lynch's Crater, oxidation-resistant elemental carbon (OREC) results were generally in accord with those of microcharcoal (Turney et al. 2001d) but were less interpretable in relation to vegetation, whereas correspondence between OREC and microcharcoal results was limited to only parts of the Lombok Ridge marine record near northwestern Australia (Wang et al. 1999). One of the more successful applications of OREC was where $\delta^{13}C$ values for different size OREC fractions (<125 and >125 μm) were obtained through a sedimentary profile at Allen's Cave, Nullarbor Plain, South Australia (Turney et al. 2001c), providing a measure of burning over the past 45,000 years and associated vegetation and climate change. The curves generated from both size fractions parallel one another and indicate increased fire frequency in the area into the Holocene. Furthermore, the high elemental $\delta^{13}C$ values recorded from approximately 45,000 to 12,000 years ago are typical of plants in moisture-limited environmental conditions, providing an indication of greater aridity (compared to present) persisting in this area. The onset of the Holocene is marked by a shift to lighter values representative of wetter conditions, probably as a result of postglacial marine transgression and closer proximity to the coastline.

Fire Scars

The most certain evidence for the occurrence of individual past fires is the presence of fire scars in some woody plants that are capable of surviving burning. Methods for deriving fire histories from an analysis of fire scars in relation to annual growth have been applied to eucalypts, especially those at high altitudes (e.g., Banks 1989), and to grass trees (*Xanthorrhoea* spp.) in Western Australia (e.g., Ward et al. 2001, Lamont et al. 2003; but see also Enright et al. 2005) and elsewhere (Mooney & Maltby 2006). These results have established estimates for general trends in burning patterns extending back into the pre-European period and baseline data on Aboriginal fire regimes. They have also demonstrated regionally distinctive and constantly changing fire patterns imposed by Europeans. Their focus has been vegetation management and it is uncertain if these data contain a significant signal of annual or interannual climate variation. The correspondence, however, between results from the alpine fire scar study and the top part of a high-resolution microfossil alpine core, which extends to 1000 years before present (Dodson et al. 1994), illustrates the potential for establishing fire-climate patterns prior to European arrival.

METHODS WITH POTENTIAL FOR ELUCIDATING FIRE-VEGETATION-CLIMATE RELATIONSHIPS IN AUSTRALIA

Long-term records and simulation approaches assist in our understanding of the roles of natural climate variability and human interaction on vegetation regimes and fire activity in Australia. However, in large part, these approaches have not been exploited to the extent possible in understanding the drivers of the fire record. The application of eggshell calcite, pollen, climate models, and fire models to elucidate fire-vegetation-climate interactions are discussed below.

Carbon Isotopes in Eggshell Calcite

Miller et al. (1999) and Johnson et al. (1999) have assessed the carbon isotopic concentration ($\delta^{13}C$) of emu eggshells (*Dromaius novaehollandiae*) from Lake Eyre, South Australia, to develop a proxy for palaeovegetation over the past 65,000 years. The eggshell calcite reflects the isotopic composition of the bird's herbivorous diet, consisting of leaves, shoots, fruits and flowers of trees, shrubs, forbs (a broad-leafed herb), and grasses. Variations in the $\delta^{13}C$ values of emu eggshells therefore reflect changes in their diet, which is ultimately driven by changes in the isotopic composition of the flora. Hence Miller et al. (1999) and Johnson et al. (1999) hypothesize that $\delta^{13}C$ in emu eggshells from Lake Eyre reflects changes in the relative proportion of C_3 to C_4 vegetation and therefore serves as an indirect proxy for the predominant season of rainfall during the past 65,000 years. It is important to note, however, that paleovegetation records in the Australian interior are sparse, particularly before 18,000 years ago.

Pollen

Pollen records can demonstrate dramatic changes in vegetation on timescales spanning hundreds of millennia, much of which can be related to global forcing. For example, Kershaw et al. (2003a,b) used pollen records from ODP Site 820 and Core GC-17 (**Table 1**, **Figure 1**), which cover the past 250,000 and 100,000 years, respectively. A decline in drier araucarian forest elements and an increase in sclerophyll components (particularly *Eucalyptus* and *Melaleuca*) indicate drier climatic conditions approximately 130,000 years and 36,000 years ago, corresponding with highest recorded microcharcoal peaks and inferred highest levels of fire activity. Kershaw et al. (2003b) also used pollen from two additional sites: Lombok Ridge core G6-4 and Banda Sea core SHI-9014 (**Table 1**, **Figure 1**). Records from the Lombok Ridge site are estimated to cover the past 290,000 years, whereas those from the Banda Sea record cover an estimated 174,000 years. Only this latter record is considered to be continuous and provides good chronological control.

Singh et al. (1981) used pollen records at Lake George in New South Wales (**Figure 1**) to reconstruct the vegetation of the area and detected a change to the sclerophyll-dominated landscape approximately 130,000 years ago; they suggested that this was due to enhanced fire activity. This burning extended into rainforest around Lynch's Crater in northeast Queensland approximately 45,000 years ago. Luly (2001) also used fossil pollen data to investigate the decline of fire-sensitive *Callitris* woodlands at Lake Frome and Lake Eyre during the late Pleistocene and Holocene. Today, situated within arid regions of inland South Australia, Lake Frome and Lake Eyre are dry most of the time. The period approximately 40,000 years ago is the only time where it can be demonstrated with a high degree of confidence that fire was influential in changing the vegetation cover. Whether this change had any large-scale feedbacks to climate remains an open question that may be addressed through modeling approaches.

PMIP: Paleoclimate Modelling Intercomparison Project

LGM: Last Glacial Maximum

MUGCM: Melbourne University general circulation model

Climate Models

Climate system models continue to improve their ability to simulate global- and many regional-scale features of contemporary climate. It is important to note, however, that often the results of contemporary climate studies can be model dependent. Experimental protocols that include the generation of ensembles and superensembles (involving multiple models) and that employ factorial designs serve to increase our confidence in the representativeness of their results (Görgen et al. 2006). Some of these approaches are now making the transition to the study of paleoclimates through broad model intercomparison initiatives such as PMIP (Paleoclimate Modelling Intercomparison Project, **http://www-pcmdi.llnl.gov/pmip**; Harrison et al. 2002) and in individual research projects (e.g., Rivers & Lynch 2004).

Climate models have been used to understand past climates specifically in Australia, but these have not focused on the mechanisms for or effects of fire. For example, the atmospheric general circulation model of the Bureau of Meteorology Research Center with T47 resolution ($2.5^\circ \times 2.5^\circ$) was used by Wyputta & McAvaney (2001) to investigate the influence of different vegetation distributions on the atmospheric circulation during the Last Glacial Maximum (LGM). These experiments demonstrated that, in this model, expansion of dryland vegetation caused an additional annual cooling of 1–2°C for Australia, whereas in Indonesia the LGM vegetation led to an increase in temperature of 0.5–1.5°C and a 30% decrease in precipitation owing to a reduction of the tropical rainforest. This was accompanied by a 30% increase in precipitation over the western Pacific Ocean. These studies provide evidence that Australian climate may be sensitive to changes in the land surface.

Miller et al. (2005) used Genesis version 2, a relatively low-resolution (T31 or $3.75^\circ \times 3.75^\circ$) atmospheric model coupled to a multilayer land surface model and a 50-m-thick "slab" ocean. An interactive predictive vegetation model was used to determine vegetation attributes at 10,000 years ago, and additional experiments evaluated the sensitivity of the Australian monsoon to vegetation and soil type. They found that penetration of monsoon moisture into the interior was sensitive in this model to the biosphere-atmosphere feedbacks associated with these parameters. As results from more modeling studies become available, the sensitivity of Australian climate to the land surface state will be better quantified.

Wardle (2003) used the Melbourne University general circulation model (MUGCM), an R21 (3.25°lat $\times$ 5.625°lon) atmospheric model, in 20-year

PMIP-type simulations of the LGM. The characteristics of surface anticyclones over the Southern Hemisphere were examined using a vortex tracking scheme, which suggested a poleward displacement of surface westerlies over much of the hemisphere during the summer and winter seasons during the LGM, compared with the present day. The largest displacement occurred over Australia during southern winter, with the anticyclone activity also reflecting a weaker tropical circulation and more intense midlatitude eddy activity during the LGM, which is in agreement with paleoreconstructions (Harrison & Dodson 1993).

FOAM: Fast Ocean Atmosphere Model

DGVM: dynamic global vegetation models

LPJ-DGVM: Lund-Postdam-Jena dynamic global vegetation model

Marshall & Lynch (2006) used the Fast Ocean Atmosphere Model (FOAM) to investigate the variation of the Australian summer monsoon during the late Quaternary. Interhemispheric forcing and the seasonal timing of local insolation changes play key, and interacting, roles on the evolution and intensity of the monsoon. The relative importance of the low-pressure pull and the high-pressure push that maintain the monsoon circulation varied according to the strength of the pressure anomalies in each hemisphere. Only in the middle Holocene was the low-pressure pull found to be the dominant forcing mechanism.

Fire Models

Fire has far-reaching implications for the climate system through effects on vegetation dynamics, biogeochemical cycling, and atmospheric chemistry and therefore there has been effort into including the dynamics of fire into climate models. Most climate models are able to derive fire danger (i.e., the meteorological potential) and thereby determine a probable fire regime. However, the impact of fire on vegetation communities is not often simulated. A capacity is developing in the international scientific community to simulate climate-fire-vegetation interactions within Earth System Models by employing dynamic global vegetation models (DGVMs) and dynamic fire models (Spessa et al. 2003). An example of one such state-of-the-art model is the Lund-Postdam-Jena DGVM (LPJ-DGVM) (Sitch et al. 2003, Thonicke et al. 2001), a biogeochemistry-based dynamic vegetation model that simulates ecosystem carbon, nitrogen, and water interactions in the context of vegetation compositional changes of various plant functional types during stand development or recovery from a disturbance. Generally, coupled fire models use observations to derive the relationship between daily litter moisture status and the length of the fire season. Observed data are also used to calibrate the relationship between the length of fire season and annual area burned. The fire model compares favorably to observational fire return intervals from Kakadu National Park in Northern Australia (Thonicke et al. 2001), but DGVMs in general continue to find the regional details of vegetation distribution challenging (e.g., Foley et al. 2000). These details can have an important impact on simulated climate in coupled models (Lynch et al. 2003). The current challenge remains in simulating both natural and human ignition sources. Current models are calibrated against known fire regimes, but clearly, to investigate future changes in fire frequency and the interactions with vegetation and climate, the human-induced fires must be quantified (Venevsky et al. 2002). Hence, although Bonan et al. (2003) incorporated vegetation dynamics from the LPJ-DGVM to the U.S. National

Center for Atmospheric Research land surface model, the expectation that this will allow integration of atmospheric and ecological processes across multiple timescales is yet to be demonstrated. Nevertheless, the development of dynamic vegetation models that include fire is one useful pathway to link our current climate modeling to both contemporary observations and paleo datasets.

HISTORY OF FIRE-VEGETATION-CLIMATE RELATIONSHIPS IN AUSTRALIA

Fire has been a long-established feature of the landscape in Australia, with episodes of enhanced fire activity and changes in fire regimes apparent in paleoenvironmental records. The recognized importance of fire as an environmental variable within the Australian region has resulted in the construction of fire histories around and within the Australian continent. By far, the majority of biomass burning studies have utilized microcharcoal particles, quantified in association with pollen from sediment sequences. Early work from the beginning of the 1980s primarily addressed the impact of Aboriginal burning on components of the Australian vegetation (Singh et al. 1981, Kershaw et al. 2002).

Despite the adoption of a variety of charcoal preparation, counting, and portrayal methods, some consistent pattern of biomass burning in relation to vegetation and climate change emerged for the Cenozoic, and particularly for the late Quaternary period. Although fire has had a long history in the Australian environment, it has become progressively more important since the mid-Tertiary, with an associated development of the characteristic sclerophyll flora and vegetation, probably as a result of increasingly dry and variable climatic conditions (Barlow 1994). Despite the existence of only two discontinuous records spanning much of the Cenozoic period, from the Murray River catchment and the Latrobe Valley of eastern Victoria (Kershaw et al. 1994), it can be concluded that major sclerophyll vegetation types with characteristic fire regimes were extensive by the beginning of the Quaternary period, some 2 million years ago. The bulk of information relates to the later part of the Quaternary (Kershaw et al. 2002): For example, currently only approximately half of the studies in the Australian paleofire database extend beyond the mid-Holocene, and only 15% extend beyond the LGM (**Table 1**).

There is a great deal of variation in charcoal representation and presumed burning levels in relation to glacial-interglacial cyclicity. In general terms, burning levels relate to fuel availability, with the lowest values occurring under very dry conditions when or where the vegetation is too open to carry frequent or intense fires and under very wet conditions owing to the nonflammability of perpetually moist, dense rainforest vegetation. A more refined relationship between climate, burning, and vegetation has been established for the Holocene in southeastern Australia, with lower charcoal values during the climatic optimum between approximately 7000 and 5000 years ago than before and after this time, despite little apparent variation in vegetation. It is considered that rainfall variability is an additional important influence on fire activity. Furthermore, temporal patterns of charcoal production, which may relate to fire activity, are somewhat different in sites surrounded by contrasting types of vegetation. On both glacial and Holocene scales, peaks in charcoal often accompany transitions between vegetation types, suggesting that burning is facilitated by times of climate change and environmental instability (Black & Mooney 2006).

ENSO: El Niño Southern Oscillation

A summary of the principal factors, climate and humans, and their role in the history of fire in the Australian landscape is given below. During some periods, the different factors may be interrelated, preventing the identification of a single control.

Influence of Climate

Research within the past few years has focused on analysis of microcharcoal records in relation to orbital and millennial-scale climate forcing especially within northern Australia. The construction of accurate chronologies for marine records by comparison with the oxygen isotope SPECMAP curve (Martinson et al. 1987) has allowed examination of the relative influence of global and regional insolation influences (Kershaw et al. 2003a). Spectral analysis has demonstrated that there are significant frequencies in charcoal variation at eccentricity (approximately 100,000 year), obliquity (approximately 40,000 year), and precessional (approximately 20,000 year) timescales, although these are not consistent between records across the region. The association of charcoal with climate is not as strong as for many pollen attributes, possibly a function of the less direct forcing by climate on burning than on vegetation. Climate creates the conditions for potential fire activity, but a broad range of factors determine whether or not a fire occurs (Krusel et al. 1993). In some records, it appears that there is little relationship between temporal patterns of burning and vegetation. In a palynological record off the Kimberley coast (MD98-2167, **Figure 1**), variation in the tree density of savanna vegetation is clearly related to precessional-scale cyclicity in Southern Hemisphere insolation; the latter appears to control monsoon rainfall in this area, whereas the charcoal signal is dominated by the global glacial-interglacial pattern that is driven by Northern Hemisphere insolation. Examination of modern pollen and charcoal in a suite of marine core top samples from the region (van der Kaars 2001, van der Kaars & de Deckker 2003) suggests that these different pollen and charcoal signals are real and cannot easily be explained by differences in mode or distance of particle transport.

In several records (e.g., MD97-2141 and ODP-820; **Figure 1**), an additional 30,000-year cycle is evident, which has been hypothesized to result from an El Niño Southern Oscillation (ENSO) modification of the precessional cycle within the Pacific region (Beaufort et al. 2003). This signal is very pronounced in charcoal and in rainforest conifers in marine record ODP-820, which is heavily influenced by the ENSO signal (Moss 1999, Moss & Kershaw 2000). Peaks in charcoal relate closely to times of maximum frequency of both El Niño and La Niña events, as inferred from the Zebiak-Cane coupled ocean-atmosphere paleoclimate model (Clement et al. 1999) with major reductions in rainforest conifers associated with the greatest peaks, at approximately 130,000 and 40,000 years. This model has demonstrated contemporary ENSO forecast skill up to two years in advance (Chen et al. 1995). It has been proposed that the peak in activity at 130,000 years ago was a result of high burning levels associated with a combination of increased climatic variability and low precipitation at the end of the penultimate glacial period. In contrast, a combination of both high climatic variability (predicted by the Zebiak-Cane model) and the presence of people (supported by the archaeological evidence) appears to have caused the peak activity centered at 40,000 years ago.

ABA-SC: acid-base-acid stepped combustion

The onset of ENSO as a key component of climate variability could date from approximately 300,000 years ago when there is evidence from the same core of a systematic shift to lighter values in the oxygen isotope record, which has been interpreted as a result of an increase in sea surface temperature (SST) of 4°C (Peerdeman et al. 1993). The most likely cause of such a shift is the development or expansion of the West Pacific Warm Pool. This may have caused alterations in oceanic and atmospheric circulation and led to the development of contemporary climate-fire-vegetation relationships within the northern Australian region.

The proposal that fire activity was reduced in more arid areas during drier glacial times was tested through palynological investigation of the marine core GC-17 (**Figure 1**) (van der Kaars & De Deckker 2002, Kershaw et al. 2003b). The results were surprising in that charcoal values were high and variable during the earlier part of the last glacial period, from approximately 100,000 to 40,000 years ago, but from then on were much reduced in magnitude and variability. Resolution of the influence of insolation has been inhibited by a relatively poor oxygen isotope record. It was hypothesized that the altered charcoal signal corresponds to a change from eucalypt woodland to more open chenopodiaceous scrub, which may suggest a sustained reduction in monsoon influence (Johnson et al. 1999), but the relative importance of human and climate influences on this change cannot readily be determined.

Recent research on suborbital timescales has been undertaken within the humid tropic region of northern Queensland at the volcanic site of Lynch's Crater (**Figure 1**). Reexamination of the uppermost part of this sedimentary sequence in association with newly determined radiocarbon ages using acid-base-acid stepped combustion (ABA-SC) has produced a robust timescale (Turney et al. 2001a) that has allowed the resolution of fire patterns in the area over the past 50,000 years. Short-term variations in charcoal have been related to inferred ENSO-forced moisture conditions on the swamp surface, with a significant periodicity of 1500 years (Turney et al. 2004). Interestingly, this periodicity matches, in both frequency and phase, warm phases within the Greenland ice cap, suggesting a Pacific ENSO link with the North Atlantic (and therefore global) millennial-scale climatic oscillations. Longer-term oscillations in the charcoal record have also been detected that could be related to ENSO forcing on a semiprecessional timescale, a frequency also present in climate records from the North Atlantic region. It was not until approximately 40,000 years ago that burning became effective in initiating the replacement of rainforest by sclerophyll vegetation, and this corresponds with a phase of high ENSO activity. The whole vegetation transition took approximately 20,000 years, and rainforest destruction only occurred during phases of inferred high ENSO activity (inferred by a range of wet-dry proxies preserved in the sediments).

The records of burning preserved in Queensland soils (Hopkins et al. 1993) are significant to climate. These are only evident from 27,000 years ago, long after initiation of burning at Lynch's Crater. It may be surmised that this signal, commencing at the beginning of the LGM, was the result of a broad regional decline in rainfall. Most soil charcoal ages fall between 13,000 and 8000 years ago, consistent with maximum drying around Lynch's Crater. Expansion of research to the humid lowlands indicates survival of sclerophyll vegetation, at least in patches, until near present, most probably indicating the persistence of Aboriginal burning during wet Holocene conditions. There was, however, a significant reexpansion of sclerophyll vegetation within the past 4000 years, consistent with the ENSO signal from sediment-based records.

A detailed record from Lake Euramoo (**Figure 1**), covering the past 20,000 years (Haberle 2005), shows low levels of charcoal during the dry glacial period, presumably the result of a lack of fuel in the open woodland vegetation. From approximately 13,000 years ago, microcharcoal increases; the values peak between approximately 11,000 and 9000 years ago in association with increased rainfall and an inferred vegetation change to wetter sclerophyll forest. This pattern is similar to that recorded from nearby Lake Barrine (Walker & Chen 1987). Microfossil charcoal declines sharply as rainforest becomes the dominant vegetation in the catchment, but it is replaced by high levels of macrocharcoal that persist to approximately 7000 years ago, possibly representing the close proximity of wet sclerophyll forest or burning on the swamp surface as a result of human activity. Burning levels remained low until approximately 4000 years ago when increased microcharcoal levels suggest an increase in ENSO-induced climatic variability. The arrival of Europeans is marked by a further sharp increase in burning that relaxes with the establishment of settled agriculture. A high-resolution record through the past few hundred years, supported by a robust lead-210 chronology, has allowed the tentative association of individual fire peaks with historically recorded ENSO events and recognition of likely events before this time (S.G. Haberle, personal communication).

Influence of Humans

In the north of Australia there is evidence of human habitation from approximately 60,000 years ago (Roberts et al. 1990, 1994). Across the rest of the continent, evidence of human occupation has been found from between 50,000 and 48,000 years ago (Turney et al. 2001b, Bowler et al. 2003). Hence, substantial vegetation and charcoal changes approximately 130,000 years ago (Singh et al. 1981) may not have been caused by anthropogenic burning, but rather by high ENSO activity that resulted in particularly dry conditions at the height of the penultimate glacial period (Kershaw et al. 2003b).

Superimposed on the general trend toward increased burning through the most recent glacial cycles, which are most likely climate induced, are clear regional shifts in fire frequency around 45,000 years ago, approximating the likely time of initial human occupation of the continent (Kershaw et al. 1997, 2006). Such shifts are also evident during the period of European colonization. This raises the following question: Is there a direct and detectable influence of human habitation on past fire regimes?

Miller et al. (1999) and Johnson et al. (1999) suggested that a reduction in shrub cover approximately 50,000 to 40,000 years ago could be attributed to Aboriginal use of fire, largely on the basis of the lack of evidence for global climate forcing at this time. They further postulated that this led to changes in moisture characteristics and a consequent decrease in the intensity of the summer monsoon over the center of Australia (Miller et al. 2005). However, the evidence for any change in vegetation and fire from records in eastern Australia is equivocal at this time.

The charcoal from MD97-2141 was analyzed as a proxy for winter monsoon strength moderated by ENSO, with high charcoal levels suggested as a proxy for reduced monsoon activity during the austral winter. A major feature of the record was a large peak in charcoal approximately 51,000 years ago, with high values sustained through the last glacial period. This feature has been related to the timing of early human settlement in the Australian region (Ambrose 1998, Turney et al. 2001b, Kershaw et al. 2006).

Singh & Luly (1991) presented a reconstruction of paleoclimatic and vegetational change at Lake Frome in South Australia (**Table 1**, **Figure 1**) using pollen analyses, which indicated changes in the amount and seasonal distribution of Australian monsoon rainfall during the late Quaternary. They attributed these changes to climate but suggested that human occupation may have had an influence. At Lake Frome, *Callitris* was prominent between 16,000 and 13,000 years ago, after which time it declined to low modern levels from approximately 11,000 years ago. Luly (2001) also investigated the disappearance of fire-sensitive *Callitris* woodlands at Lake Eyre. Here, *Callitris* became apparent again after the LGM, from 10,000 years ago until approximately 5000 years ago, before vanishing from the pollen record. Despite ambiguities in the charcoal record, the decline of *Callitris* at both sites broadly corresponds with archaeological indications of increasing human presence in the landscape, lending support to the proposition that indigenous fire practices modified the vegetation around Lake Eyre and Lake Frome.

Some emphasis has been placed on attempting to decouple the roles of climate and people on vegetation and fire patterns within the Holocene, a period that experienced the latest phase of high ENSO activity (Clement et al. 1999, McGlone et al. 1992, Rodbell et al. 1999, Sandweiss et al. 1996, Moy et al. 2002). Black & Mooney (2006) described the influence of climate on human society and thereby on fire regimes, coupled with the direct role of climate on fire activity, as a “complex nexus”. Results from multiproxy analyses (including microcharcoal and pollen) and dating of archaeological sites (Haberle & David 2004, Tibby et al. 2006, Turney & Hobbs 2006) all show increases in charcoal in relation to an intensification of human settlement and cultural development between approximately 5500 and 3750 years ago, although this appears to have been precipitated by the loss of stability in resource availability resulting from increased climatic and environmental variability. In contrast, Black et al. (2006) found no association between archaeological indices and macrocharcoal at a site in the Sydney Basin.

There have been a number of studies focused on the impact of European arrival on the fire regimes of southeast Australia. Studies conducted on billabongs associated with investigation of river water quality (e.g., Leahy et al. 2005; M.A. Reid, C.D.

Sayer, A.P. Kershaw, H. Heijnis, manuscript in review) appear to demonstrate that intense burning accompanied early colonization, which would have differed in timing from place to place. Problems with dating these sediments and probable sediment mixing owing to flooding events have inhibited the determination of precise and accurate ages for high fire activity.

There have been a limited number of studies focused on the impact of European arrival on the fire regimes of southeast Australia (e.g., Gell et al. 1993, Dodson et al. 1994). To date, no Australian study has attained a sufficient resolution of analysis to investigate the influence of climatic variability on fire activity during the historic period. For example, investigating the influence of changes to ENSO behavior on fire during the late twentieth century (Gergis & Fowler 2006) is a challenge that has yet to be realized in Australia. A better understanding of the relationship between charcoal and fire should also eventuate from investigating the deposition of charcoal in sediments from historic fires (Clark 1983).

CONCLUSIONS

Assessment of Methods

The most generally applicable methods to determine past fire activity are the quantification of microcharcoal and chemical analysis of elemental carbon, as these can be applied to any sedimentary deposit and related to source vegetation through pollen analysis. They are also the only methods available for marine cores that lie some distance from vegetation sources. The results from microcharcoal analysis are generally easier to interpret than those derived from chemical analysis. Long records with good chronological control (marine isotopes in marine cores and radiocarbon dating of chemically cleaned charcoal with stepped combustion) have provided valuable insights into vegetation-fire-climate relationships on orbital and millennial timescales and have allowed some separation of natural and human burning patterns. Results are approaching the stage where they can be used in the generation and testing of models designed to explain features that have led to the development of the Australian landscape, such as the impact of people (including megafaunal extinction) and feedbacks on the climate system. Ultimately, such models have great promise for determining the causes of periods of high fire activity.

Microcharcoal, however, is generally limited owing to uncertainties about the spatial scale of sources (e.g., Clark 1988) and in its ability to record individual fires or fire frequencies. Although fires are of limited duration, charcoal remains on the landscape and is subsequently washed into depositional sites to provide a long-lasting background signal. The degree to which microcharcoal reflects proximal or distant fires is therefore uncertain. In contrast, macrocharcoal preserved in sedimentary records potentially allows the recognition of individual fires within a specific catchment, which has led to methodological advances resulting in the statistical identification of fire frequency through time (e.g., Long et al. 1998, Hallet & Walker 2000, Millspaugh et al. 2000). These methods hold significant promise (e.g., Mooney & Maltby 2006), for example, by allowing comparison with independently derived past climates, and provide an ideal methodological and modeling approach that could be adapted to Australian conditions.

Application to Contemporary Climate

Paleoenvironmental studies have a strong potential to inform future planning through their longer temporal perspective and hence elucidation of the contemporary record and processes. The most obvious application is that past records combined with recent observations can better indicate long-term trends relevant to climate change in the twenty-first century (Nicholls et al. 2006). For example, Kershaw et al. (2003a) suggest that there will be an increase in environmental variability and enhancement in the drying trend that will continue into the foreseeable future. Such projections may be enhanced by an elucidation of mechanisms. For example, a preliminary analysis of the Kimberley coastline by Hope et al. (2004) suggests, from *Eucalyptus* patterns through the past 300,000 years, that vegetation in northwestern Australia may be dominated by the precessional forcing of the summer monsoon through orbital variations in Southern Hemisphere insolation. This could result in increased cover of eucalypts at a time when more open vegetation is predicted for the continent as a whole.

It is important to establish vegetation and fire responses to climate to allow the identification of the anthropogenic influences. This is confounded by the fact that climate change often induces human responses, just as human activities can influence climate change (Johnson et al. 1999). It is possible that human impacts can be separated from other causes through future paleoinvestigations (e.g., Kershaw et al. 2006). Methodological issues, however, remain a barrier.

The role of fire as a primary natural carbon cycling mechanism is a key issue in considering global climate change feedbacks. In particular, the partitioning of the carbon fluxes between the atmosphere and terrestrial ecosystems is important for predicting and managing atmospheric CO_2 concentrations. Although the contributions of CO_2 from burning savanna biomass are well known (Beringer et al. 1995), the effects on the savanna carbon balance following fire are virtually unknown. During the burning of a savanna, CO_2 that had been sequestered in previous seasons is suddenly released into the atmosphere in a relatively short period of time (Levine et al. 1995). As the ecosystem regrows, CO_2 is removed from the atmosphere by photosynthesis and incorporated into the new vegetative growth. Despite this, the net productivity is reduced due to canopy damage from fire (Beringer et al. 2003). Therefore, as far as savanna management is concerned, there may be potential for increasing carbon storage in ecosystems by reducing fire frequency (Hutley et al. 2005).

Finally, appropriate application of climate, fire, and vegetation to contemporary and paleoclimate realizations will allow us to better understand the feedbacks between climate change, vegetation successions, and fire probabilities, and thereby elucidate the proxy record. This has the potential to be an important tool for assessing the impact on carbon and other biogeochemical cycles. For instance, compilation of paleoenvironmental data on past fire regimes will be very useful for evaluating prognostic models of vegetation, fire, and fire emissions (Spessa et al. 2003).

Future Work

The most important priority facing Australian paleoscience today is to address the problems with the observational record in terms of quality, quantity, and dating. Methodologically, several recent advances in North America provide a template for the systematic examination of charcoal, vegetation, and climate patterns. Their results, however, relate only to the frequency of burns. There is no known method that addresses the critical question of fire intensity. At present, this can only be inferred by reference to associated vegetation derived from pollen or identified macrofossil charcoal particles and its existing fire regime, which is a circular form of reasoning. Parameters of charcoal particles such as size and morphology might be important, although existing studies overseas (Tinner & Hu 2003) suggest that size at least is not a characteristic feature of burns in different communities. In contrast, Enache & Cumming (2006) described several useful relationships between charcoal morphological characteristics and historic fires in a British Columbian study, potentially providing information on fire type and proximity.

This suggests that it is important to attempt more systematic study of vegetation-charcoal-fire relationships in Australia in an attempt to calibrate charcoal in terms of fire regimes that can be related to vegetation and climate. It is envisaged that such studies would involve detailed analysis and dating of many sediment cores to allow determination of vegetation-fire relationships before the arrival of people, to quantify any relationships with climate and to document changes in fire regimes as a result of European impact. Such studies would be time consuming, but developments in automation could alleviate much of the burden (e.g., Black & Mooney 2006). Developments in radiometric dating techniques would be advantageous, although, in many areas, the presence of exotic plants would allow recognition of initial European settlement.

As shown in **Figure 1**, there is a dearth of paleorecords over the vast interior of Australia, a function largely of discontinuous sediment sequences and concern about the degree of preservation of pollen and charcoal. However, the coverage of sites could be expanded and records covering the past few thousand years may be preserved, especially in salt lakes. More rigorous analysis of marine records that cover a good range of precipitation variation as well as climate forcing controls over the continent will allow improved recognition of the nature and extent of forcing on climate variability at Milankovich and millennial scales, but they are unlikely to reveal variation within the past few hundred years.

With better data, important open questions can be addressed. For example, Luly (2001) suggests that there is an urgent need for a better understanding of how the fire-generated mosaic of vegetation types in central Australia was maintained during the late Pleistocene. Importantly, paleorecords lack resolution (for the most part) to examine ENSO variability. Current relationships between ENSO and fire in Australia are important to understand future changes. Links between ENSO, SAM (Southern Annular Model), IPO, and rainfall regimes (monsoon, winter rainfall regimes) must be explored. These efforts can be aided by an expansion of certain areas of contemporary climate research. Contemporary observational studies to elucidate relevant processes and feedbacks may be critical in the Australian context. Such studies can address the question as to whether there are specific climatic drivers that will result in step changes in fire regimes.

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