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Pre-European Fire Regimes in Australian Ecosystems

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Abstract

We use multiple lines of evidence, including palaeo-environmental, ecological, historical, anthropological and archaeological, to investigate pre-European fire regimes in Australia, with particular focus on the extent to which the use of fire by Aboriginal peoples since their colonisation of the continent at least 45,000 years ago has impacted on the Australian biota. The relative roles of people and climate (including past climate change) as agents driving fire regime are assessed for the major climate–vegetation regions of the continent. Both historical accounts and evidence from current land-use practices in some areas support the argument that Aboriginal peoples used fire as a land management tool. Evidence for pre-European fire regimes suggests that while large areas of savanna woodlands in northern Australia, and dry forests and woodlands in temperate southern Australia, were subjected to increased fire under Aboriginal land management; others were not. Areas where fire regime was controlled primarily by 'natural' climate-fuel relationships probably included those that were difficult to burn because they were too wet (e.g. rainforests), fuel levels were usually too low (e.g. desert and semi-arid rangelands), or resource availability was low and did not support other than transient human occupation (e.g. some shrublands). Scientific studies suggest that many fire-sensitive woody species would decline under more frequent burning, so that the use of a small patch size, frequent fire regime – such as may have existed over large parts of Australia in the pre-European (Aboriginal occupation) period – may have harmful biodiversity conservation outcomes if instituted without careful consideration of individual ecosystem and species requirements.

Introduction

Increasing size and severity of wildfires has been reported for both North American and Australian fire-prone ecosystems over recent decades and has promoted debate concerning the appropriateness of current terrestrial ecosystem management practices on both continents (Esplin et al. 2003; Whitlock and Knox 2002). Higher temperatures and increased frequency of extreme weather events as global warming proceeds through the 21st century are predicted by global climate models, leading to a likely further increase in the frequency of large, high-severity fires (Cary 2002). In southeastern Australia, extreme drought conditions associated with a strong and persistent El Niño supported wildfires that burned >1 million hectares of forest in each of the summers of 2002–2003 and 2006–2007. Events of similar magnitude have affected forest areas in western North America in the years 2000, 2004 and 2007, respectively.

European settlement of Australia is generally accepted as commencing in 1788 with arrival of the First Fleet at Botany Bay (Sydney). British colonies were established in all states by the 1830s, supporting a sustained and massive impact on the environment through land clearance for agriculture and grazing, the introduction of new crops and animals, and the displacement of native peoples and their traditional uses of the land. Large fires resulting in significant loss of property and/or human life have punctuated the history of settlement, most notably in southeastern Australia in 1851, 1939, 1983, 2003 and 2007. The managed use of fire to reduce fuel loads in public estate forests (and other vegetation types) since the 1950s has been the major strategy employed by government to mitigate the risk of unplanned fire spreading into private lands (Esplin et al. 2003). Despite this 'prescribed burning' programme, large unplanned fires in 1983, 2003 and 2007 have cast doubt over its effectiveness. Changes in vegetation and fuel loads following European settlement of New World continents have been attributed to the displacement of native peoples and their traditional land-use practices (Pyne 1982), and subsequently through evolving policies of fire suppression, conservation estate management, and health and safety regulation of fire-fighting procedures (Esplin et al. 2003). The increasing impact of unplanned fires on people is also a consequence of post-European settlement patterns and land uses, with associated high asset values and fragmentation of the landscape into a mosaic of private and public lands with very different management goals and requirements (Esplin et al. 2003).

Critics argue that there has been insufficient prescribed burning to provide an effective barrier to the spread of unplanned fires, noting that current 'burn area' targets have rarely been met in most Australian states over the past two decades [for example, see media releases and policy statements from the Victorian Farmers Federation (www.vff.org.au) and Mountain Cattlemen's Association (www.mcav.com.au)]. One suggested remedy is an increase in prescribed burning to meet more stringent asset protection and/or ecological targets established by the relevant state agencies responsible for fire mitigation and management. Others suggest the institution of a fire management policy that mirrors the pre-European, 'Aboriginal burning regime', using a patchwork of frequent, low-intensity fires across all public lands to manage fuel loads (e.g. Ward et al. 2001).

Vale (2002) and other contributors (e.g. Baker 2002; Whitlock and Knox 2002) provide an overview of these issues for western North America in the context of the 'pristine versus humanised landscape' debate. While fire is acknowledged as a major, natural disturbance factor in these ecosystems, debate focuses on whether native peoples used fire to the extent that it had fundamentally changed fire regimes, and the vegetation associated with them, by the time of European settlement (Vale 2002). The story in North America is perhaps more complex, and yet more tractable than it is in Australia. The history of European settlement there is longer and more varied, with Spanish contact in the south and west from around 1500, and French and British contact spreading from the east from the 1600s. Introduced diseases reduced native populations massively in some areas ahead of the invading front of European settlers, while cultural changes (including in the use of fire) are likely to have accompanied domestication of the horse by some native tribes. While it is not clear to what extent that these impacts altered vegetation and fire regimes during this early contact phase (noting that the accounts of early explorers and settlers cannot resolve this), reconstruction of fire regimes (and climate variability) using tree-ring analysis has provided many chronologies dating back into the pre-European period that provide evidence of the fire regime for many vegetation types and geographical locations. The large size of the scientific community involved in such research, and the ability of tree-ring studies to identify weather conditions (e.g. drought) and season of fire, allows for a more detailed scientific treatment of the case for natural versus human landscape than is the case in Australia. In the latter, there are few tree species that show annual tree-ring production sufficient for accurate historical reconstruction, and such species are restricted in their geographical extent. On the other hand, extant Aboriginal communities in northern and central Australia are still well connected to the land and manage many areas in co-operation with government agencies using traditional fire management practices.

Here, we explore:

- whether Aboriginal peoples changed the distribution, structure and composition of Australian vegetation through their use of fire following colonisation of the continent around 50 ka before present (BP);
- whether most or all vegetation types and areas were affected by such anthropogenic fire regimes in the pre-European settlement period; and
- the relevance of traditional fire regimes to the objectives of modern fire management for Australian vegetation.

Fire and the Australian Biota Prior to the Arrival of People

That fire was important in pre-human Australia is evident in the range of adaptations to fire observed in the floras of extant fire-prone plant communities, with many species able to regrow vegetatively after fire from protected buds (either above or below-ground), serotiny (seed storage in a canopy seed bank), fire-stimulated flowering, and heat- and smoke-stimulated germination of soil-stored seeds (Gill 1981).

Various prominent Australian plant families, including the Proteaceae and Myrtaceae, were major components of (primarily tropical) Australian Eocene floras, with sclerophylly most likely a response to low fertility soils rather than to seasonality of rainfall and aridity. Scleromorphous elements in the flora increased through the Oligocene (45–25 Ma BP) as the climate dried (Kershaw et al. 2002). Evidence for fire appears unequivocally towards the end of the Miocene (about 10–6 Ma) as fossil charcoal in southeastern Australian deposits, and since at least 1.4 Ma BP as abundant charcoal particles in deep-sea core ODP-820 off the coast of north Queensland, indicative of the regional presence of frequent fire (Kershaw et al. 1993, 2002). Pollen and charcoal analyses of two small sections of varved sediments from a Pliocene-aged deposit (estimated 3.2 Ma) near Yallalie, southwestern Australia, reveal a record indicating the occurrence of fires, probably close to the sample site, with a mean return interval of 6–10 years in vegetation interpreted to represent a mosaic of dry rainforest (including Araucariaceae) and sclerophyll woodland dominated by Casuarinaceae and Myrtaceae (Atahan et al. 2004; Dodson et al. 2005). Dodson et al. (2005) concluded that, although fire was common, fire intervals were longer – and perhaps more variable – than today. Singh and Geissler (1985) report the regular occurrence of fire back to 800 ka BP at Lake George in southeastern Australia, increasing especially after 140 ka BP, probably in association with intensification of El Niño–Southern Oscillation (ENSO) climate variability that shows peaks around 130 ka BP and 40 ka BP (Kershaw et al. 2003).

These authors, and others, argue that fire has increased as a factor driving evolution and adaptation of the Australian biota (plant and animal species) since the mid- to late Tertiary, accompanying increased aridity and the onset of the glacial–interglacial cycles of the last two million years, and long pre-dating human presence on the continent. Glacials were generally drier with more open vegetation dominated by Poaceae, Asteraceae and Chenopodiaceae, and charcoal abundance (evidence of fire) markedly reduced in much of temperate Australia where increased aridity limited fuel availability (Hope et al. 2004). On the other hand, in parts of tropical Australia, charcoal levels (and fire) increased as fire-prone savanna vegetation replaced areas of wet forest and the effectiveness of the summer monsoon decreased. A range of global and regional insolation factors are correlated with charcoal fragment abundance in long ocean-core sequences from northern Australia and Southeast Asia, suggesting real climate-driven variations in the occurrence of fire at time scales of thousands and tens of thousands of years. Lynch et al. (2007) provide an up-to-date review of these factors, and of the methodological limitations associated with the use of microcharcoal in sediment deposits as a measure of fire: while charcoal provides a long-lasting background signal of fire, it may be transported over considerable distances, and the relationship between charcoal abundance and the frequency, intensity and proximity of fire is not a simple one (Clark 1988; Lynch et al. 2007).

Prior to the arrival of people in Australia, almost all ignitions would have been the result of lightning. The importance of lightning as a cause of fires in new world landscapes was greatly underestimated during the early phases of European settlement, with many 19th-century reports by explorers and others discounting it as an ignition source relative to human agency (e.g. Baker 2002). Only with the growth of modern meteorological science in the 20th century, and the more recent advent of ground- and satellite-based lightning detection instrumentation, has more accurate data become available on the numbers of lightning strikes per unit area per year, and on the numbers (and proportion) of fires started by lightning.

The modern frequency of ground-flash lightning strikes in Australia shows a strong north to south gradient, with highest values (up to 8 km^{-2} $year^{-1}$) in the tropical northwest and lowest values (~0.5 km^{-2} $year^{-1}$) in southern Australia and Tasmania (Kuleshov et al. 2006). Values are generally low through arid central Australia (0.5–2 km^{-2} $year^{-1}$) and moderate along the eastern coastline (2–3 km^{-2} $year^{-1}$). Lightning strikes tend to show a positive correlation with elevation (e.g. Baker 2002; Kilinc and Beringer 2007), although this is not important in many parts of Australia due to the subdued topography. The conversion of ground-flash strikes to fires is dependent on the duration of the strike and the condition of the vegetation (fuel) at the time. In northern Australia, Kilinc and Beringer (2007) reported that lightning strikes were most frequent in the dry to wet monsoonal transition period, so that lightning-started fires were most likely in the late dry season – early wet season. In southwestern Australia, McCaw and Hanstrum (2003) found that 75% of all lightning-started fires recorded on public lands in the 8-month fire season from September to April during the period 1995–2001 occurred in the 2 summer months of December and January, coinciding with dry fuel conditions facilitating ignition and fire spread.

Luke and McAthur (1978) state that 80% of fires in the semi-arid grassland and woodland ecosystems of western Queensland are caused by lightning. They also report that 'fires of enormous extent have apparently always occurred in the arid regions [of central Australia] in periods following heavy rainfalls' (Luke and McAthur 1978, 271). For example, predominantly lightning ignited fires in the summer of 1974–1975 burned a total of 117 million hectares, representing 15.2% of the continent. Other major fire events in Australia have been characterised by multiple ignitions within a single storm front: >80 fires started on the night of 7–8 January 2003 in northeastern Victoria, four of these eventually burning > one million hectares of forest and farmland (Esplin et al. 2003), while in the summer of 1960/1961 lightning started 110 fires in southwestern Australia, many during the passage of a single storm near Dwellingup that burned 146,000 hectares of forest and destroyed the town (McCaw et al. 2003). Overall, these data indicate that lightning probably provides a sufficient source of ignitions to maintain savanna, semi-arid rangeland and dry forest types, while high moisture levels probably limited the role of lightning-started fires in wet forests.

Arrival of People and Human Impacts on the Biota

Direct evidence for the arrival of people in Australia, based on radiocarbon dating of human remains, indicates colonisation of the continent at least by 40 ka BP (Allen 1994), while thermoluminescence dates from occupation sites in the Northern Territory suggest possible arrival by 60 ka BP (Roberts et al. 1993). Gillespie et al. (2006) settle on a 'most likely' colonisation date of 50–46 ka BP based on a recent re-evaluation of radiocarbon dates and measurement uncertainties.

The first Australian colonists were almost certainly already skilled users of fire before they set foot on the continent. Jones (1969) proposed the term, 'fire stick farming' as a metaphor for the purposeful burning and manipulation of plant communities by Aboriginal peoples. Within this concept are a myriad of economic, ritual, territorial and medicinal reasons for setting fires. These are not the concern of this article. Rather, we seek to understand the ecological effects of burning in terms of landscape modification, focusing on plant community structures, compositions and distributions. Conflict and misunderstanding between government land managers and indigenous land owners has inevitably occurred, because both burn for different, sometimes incompatible sets of reasons (Rose 1996). However, regardless of this, the patterns of biodiversity seen across the continent today must be interpreted in terms of natural patterns that have been overlain by >40 ka of anthropogenic fire.

Notwithstanding the debate concerning the date of first arrival, argument continues over whether Aboriginal occupation of Australia was accompanied by:

- little or no human-induced change in vegetation;
- an early phase of landscape alteration as a new land-use regime was established, followed by some sort of equilibrium that maintained a system with desired properties – a human landscape *sensu* Vale (2002); or
- continuous change (Bowman 1998).

At the time of Aboriginal arrival, Australia supported a diverse megafauna of marsupial species with body weights >40 kg, including giant forms of nearly every extant marsupial. Nearly, all of these species were extinct by the time of European settlement, archaeologists and palaeo-ecologists variously attributing these extinctions to:

- people (the Pleistocene over-kill hypothesis; Martin and Wright 1967);
- climate change (the impacts of glacial–interglacial cycles on the distribution of suitable vegetation, appropriate climate for growth and reproduction, and available water; Horton 2000); or
- a combination of the two (Bowman 1998; Dodson et al. 1992).

In context of fire, Bowman (2003) proposes a simple three-step model to describe the changing role of fire through time in relation to savanna ecosystem dynamics that may be generalised to much of the continent: (i) a pre-human period of lightning-driven fire resulting in fires of moderate to large size producing a coarse-scale habitat mosaic to which the biota was well adapted, (ii) the Aboriginal period of frequent fire, leading to small fires and a fine-scale habitat mosaic (which favoured small animals, but perhaps not the Pleistocene megafauna), and (iii) the post-European period of very large fires homogenising the landscape, leading to loss of habitat complexity and of some mammal and bird species. Here, we attempt to combine elements of the above ideas about people and environmental change, suggesting three fire regime scenarios to explain the geographical patterns of vegetation in Australia at the time of European contact:

1. Fire regimes in Australian terrestrial ecosystems are driven by climate, with little human impact on regime associated with ~50 ka of human occupation.
2. Fire regimes over the 50 ka of human occupation prior to the arrival of Europeans were largely anthropogenic, overwhelming 'natural' (climate-driven) regimes and with major impacts on the distribution and properties of vegetation types.
3. The impact of people on fire regime and vegetation over the 50 ka of human occupation prior to the arrival of Europeans varied markedly geographically, with fire regime in some vegetation types less affected than in others due to differences in the extent to which climate and fuel characteristics control the likelihood of ignitions and fire spread.

Recent meta-analyses of dates for megafaunal remains in Australian sites (Roberts et al. 2001) and for joint human-megafaunal chronologies (Gillespie et al. 2006) conclude that most megafauna present in Australia in the mid- to late Pleistocene survived until 45–40 ka BP, at which time around 90% of these species suddenly go extinct, representing a 1–6 ka overlap with people. Since this period is not one associated with major climatic change in Australia (van der Kaars and De Deckker 2002; Lynch et al. 2007), the weight of evidence supports a primarily human cause for the extinctions. These findings are further supported by evidence for a major shift in dietary $\delta^{13}C$ in fossil egg shells of the extant emu (*Dromaius novaehollandiae*) and extinct flightless bird (*Genyornis newtoni*), which disappeared around 50–45 ka BP (Miller et al. 2005): prior to 50 ka BP, $\delta^{13}C$ in egg shells of both species from arid central Australia indicated diets containing a substantial proportion of C_4 plants, while after 45 ka BP *Genyornis* is extinct and $\delta^{13}C$ in emu egg shells (through to the present) shows a major shift to a C_3-dominated diet. Miller et al. (2005) interpret this in terms of a sudden shift in vegetation from arid woodlands with nutrient-rich C_4 grasses to a fire-adapted chenopod–desert scrub and low-nutrient grasses, possibly caused by a sudden increase in fire associated with human colonisation. Nevertheless, Brook and Bowman (2002) urge continued caution, arguing that the duration of (any) overlap between humans and megafauna remains uncertain. Furthermore, although pollen and charcoal evidence from marine core GC-17 near North West Cape (van der Kaars and De Deckker 2002) supports the rapid vegetation change indicated by Miller et al. (2005), charcoal inputs decline after 40 ka BP, and do not provide strong support for ongoing human agency through fire in the landscape (see Figure 1, for locations referred to in the text). Rather, they suggest that increased aridity, and reduction in biomass to fuel fires, may have occurred due to a weakening of the monsoon. Flannery (1994) speculated that megafauna loss alone may have changed the nature of some plant communities, increasing rates of live and dead plant biomass accumulation, favouring more frequent and higher-intensity fires.

In northeastern Australia, rainforest decreased in extent rapidly only after about 40 ka BP, being replaced by fire-prone sclerophyll (*Eucalyptus*-dominated) vegetation. The timing of rainforest decline coincides with a phase of inferred high ENSO activity (Turney et al. 2004) and with the presence of people. Charcoal peaks with a periodicity of around 1500 years coincide with periods of rainforest decline over the following 20 ka. Microcharcoal levels decrease around 7 ka BP, as temperature and rainfall increases, and rainforest re-invades sclerophyll forest reclaiming lost areas of habitat regardless of the presence of humans as an additional ignition source (Kershaw 1986; Lynch et al. 2007). Charcoal levels increase again after 4 ka BP, also correlated with increased ENSO-induced climatic variability (Lynch et al. 2007).

In central and southern Australia, the decline of *Callitris* (Cupressaceae; native pine) woodlands around Lake Frome in the period 13–11 ka BP and Lake Eyre in the period 10–5 ka BP corresponds with greater variability in rainfall and with increased human presence (Luly 2001; Singh and Luly 1991). Head (1989) and Lourandos (1983) report changes in technology, and intensification of Aboriginal occupation and land use in southeastern Australia after 5 ka BP, and increases in charcoal are also generally associated with these sites. The dingo was introduced to the continent and the thylacine (Tasmanian tiger) disappeared from mainland Australia (Gollan 1984). These events all represent gradual changes in the Australian environment, shaping the nature of plant and animal communities, the people–environment relationship, and the place of fire and its effects on them.

Fig. 1. Map of Australia showing generalised locations of sites and regions referred to in the text, and major rainfall isohyets (mm). Vegetation types are closely linked to the continental scale annual rainfall pattern: tropical rainforest is found only in northeastern Queensland in regions receiving >1600 mm, and temperate rainforests in eastern and southeastern Australia and Tasmania under similar rainfall conditions. Tropical woodland savannas dominate northern Australia (10–20°S), with density of the tree layer declining as latitude increases and rainfall decreases. Central and western Australia between latitudes 20°S and 30°S is dominated by desert vegetation with spinifex (*Triodia* and *Plectrachne* spp.) hummock grasses prominent. Shrublands, extensive areas of dry sclerophyll forest, and smaller areas of wet sclerophyll (tall *Eucalyptus*) forest, become common as rainfall increases again in the more temperate regions (>30°S) of eastern, southeastern and southwestern Australia [Note: this is a simplified overview of natural vegetation patterns in Australia which ignores great variation in vegetation structure and composition within and among regions].

Pre-European Fire Regimes

SOUTHERN (TEMPERATE) AUSTRALIA

Supporting evidence for a pre-European, high-frequency, low-intensity burning regime in Australian vegetation has been based mostly on the written accounts of early European explorers and settlers (and their interpretation) and studies by ethnographers and anthropologists who have viewed Aboriginal practices in central and northern Australia in the post-European period.

There are many accounts from southern (temperate) Australia and Tasmania for the period from first European contact through to the mid-19th century. Similar accounts are recorded for central and northern Australia into the 20th century, reflecting the survival of traditional Aboriginal practices in these areas until more recently (Gill 2000). Accounts regularly describe Aboriginal people's frequent burning of vegetation, including forest understoreys, to maintain open areas of vegetation for ease of travel, to produce new growth of plants for human consumption (or for consumption by animals used by people), and to drive animals for hunting purposes (see reviews by Abbott 2003; Bowman 1998; Hallam 1975; Nicholson 1981; among others). Historical accounts also support the contention that some fires lit by Aboriginal peoples were large and of high intensity; for example, the French naturalist, Peron (on the Baudin Expedition of 1802), recounts details of a forest fire in Tasmania which 'destroyed all the herbage', 'most of the small trees and shrubs', and burned 'the tallest trees to a considerable height', some of them having fallen as a result of 'the violence of the flames' (Peron 1809, 191–192).

In southern Australia, the alienation of Aboriginal groups from their traditional lands means that repositories of this knowledge are fragmentary, and most attempts to reconstruct fire regimes have been regarded as largely speculative (Benson and Redpath 1997). The historical observation record of Aboriginal burning in southern Australia provides specific evidence on fire season since dates of fires were recorded in many cases. A synthesis of historical records for Aboriginal fires in southwestern Australia before and during early European settlement reports that most fires (74%) were lit in summer, and nearly all (86%) occurred in the hottest 4 months of the year under typically hot and windy conditions (Abbott 2003).

For cultural reasons, it is likely that certain areas were not burned, while areas infrequently occupied by people (e.g. those low in resources) may not have been regularly 'managed' using fire. In such places, natural ignition fires would be the norm, with some burning by Aboriginal peoples nevertheless likely from time to time where not precluded for cultural reasons. Specific reference in historical sources to areas being left unburned are not unusual; for example, 'Like other Aboriginal groups across Australia, Wiradjuri clans [in the Riverina District of New South Wales] reserved places where no hunting, fishing, gathering or burning was allowed' (Rose 1996, 49). It is unknown whether explicit objectives of burning included a reduced likelihood of large unplanned fires, although this is possible, because such fires could adversely affect the distribution of food resources for some time, could damage sites of cultural significance, and would be a threat to human life.

A number of early accounts describing the Australian bush note the open nature of forest and woodland understoreys and the ease with which exploration parties were able to move through the countryside in the early settlement period – see, for example, the journals of Major Mitchell

(1839) in Victoria, and of James Drummond (expeditions in the 1840s and 1850s summarised by Ericson 1969) in southwestern Australia, and reviews by Hallam (1975), Bowman (1998) and Abbott (2003). This has been ascribed to Aboriginal burning in most cases, with frequent, understorey (low-intensity) fire regime precluding the development of a dense shrub layer. However, Horton (2000) has argued that the maintenance of open, grassy understoreys by frequent fire would have favoured the large herbivores (which became extinct by 40 ka BP), and would disadvantage small ones that mostly require shrubby ground cover or log hollows for refuge, shelter and breeding. Because it was the small species that have survived better through to the present day, Horton suggests that Aboriginal burning cannot have resulted in a landscape in which grassiness was more common than shrubbiness in forest and woodland understoreys. Such frequent burning might also have limited the recruitment of tree species sufficient for long-term parent replacement.

Evidence is also available for the presence of dense vegetation in some places, and for the development of open vegetation in others, in the absence of Aboriginal burning. Gell et al. (1993) reported a mixed shrub–grass understorey associated with low-frequency fire in the immediate pre-European period for a forest site in East Gippsland (Victoria) based on pollen and charcoal analyses of short sediment cores. Grassiness increased during the early European period in association with more frequent fire, and then decreased as shrubs gained ascendancy after fire suppression was introduced to the area. Wahren et al. (1994) document changes from shrub to grass and herb dominance in the absence of fire and grazing in alpine grassland–shrubland vegetation on the Bogong High Plains, Australian Alps. Central Victoria, an area massively disturbed by mining and timber harvesting since the 1850s, appears to have been characterised by forested hills – probably Box-Ironbark (*Eucalyptus tricarpa* or *Eucalyptus sideroxylon*) forests – often with a shrubby understorey (Howitt 1855), interspersed with grassy plains (Howitt 1855; Mitchell 1839). The latter vegetation was most likely related to present-day Red Gum (*Eucalyptus camaldulensis*) grassy woodlands (see Figure 2, for a simplified vegetation map of Australia, and Figures 3–7, for images of major Australian vegetation types discussed here).

While some forested areas of southern Australia may have been affected by frequent understorey burning prior to the 20th century, this is not necessarily true of fire in shrublands. Here, fire behaviour is governed largely by the horizontal and vertical continuity of well-aerated live and dead fine fuels – either fires will spread through most live foliage, or will not spread at all (Catchpole 2002; Keith et al. 2002). The journals of three early European expeditions to pass through the mid-west region of western Australia – Grey (in April 1841) and the Gregory brothers (two trips: September 1846 and November 1848) – report frequent encounters with Aboriginals in the fertile river valleys of the Chapman (Geraldton area)

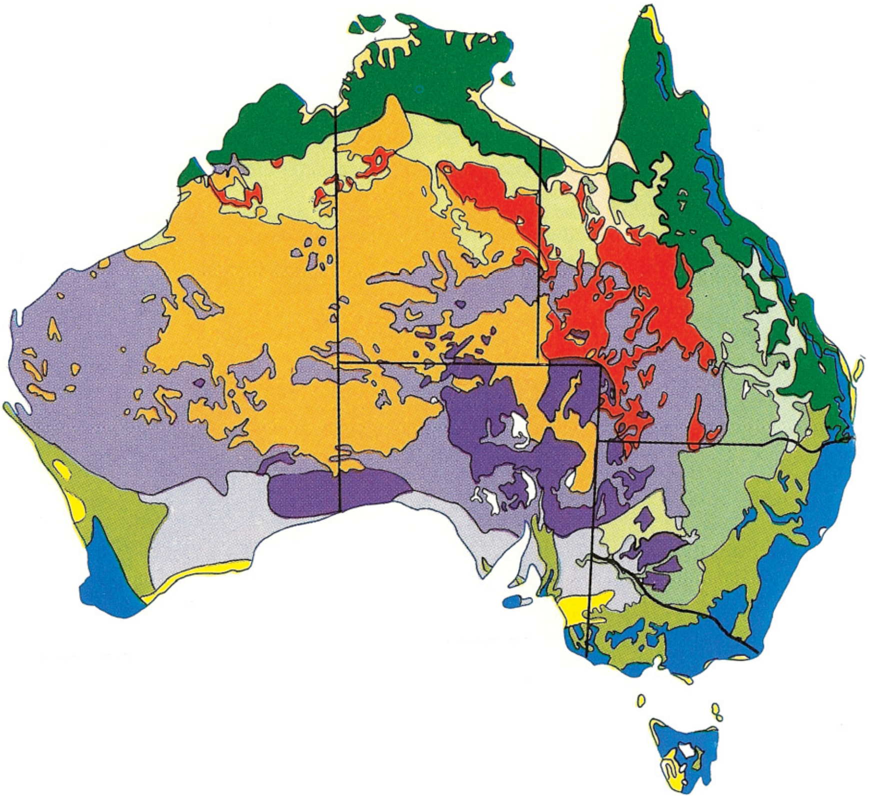

Fig. 2. Vegetation and fuel types of Australia (from Luke and McAthur 1978, 12). The major vegetation types discussed in the text include; closed forests – including both tropical and temperate (blue), tropical woodland savanna (dark green), dry sclerophyll open forests and woodlands (bright green), Mediterranean-type shrublands (yellow), and semi-arid and arid tussock (red) and hummock (orange) grasslands. Semi-arid woodlands dominated by Acacia and mallee eucalypt species are shown in mid- and light-purple, respectively.

and Irwin (Dongara area) Rivers, but encounter Aborigines only once (indirectly), through the sighting of a camp fire at night, in the extensive, biodiverse shrublands of the Eneabba sandplain further to the south.

While Aboriginal peoples certainly traversed these shrublands to move between coastal and inland areas, and may have hunted within them from time to time, the dense, prickly vegetation and relatively low resource base may not have warranted regular use of these areas and their 'treatment' with fire. The Gregory's observed that 'the [Eneabba] plain . . . produces nothing but scrub and banksia with a few grass-trees' (Gregory and Gregory 1884). Journal entries report many hours of travel on horse back through such vegetation with no mention of freshly (or recently) burned ground as might be expected if the area was characterised by a mosaic of small burn patches at frequent intervals. A similar story emerges for the

Fig. 3. Wet sclerophyll forest in southeastern Queensland, dominated by a tree layer of fire-sensitive *Eucalyptus grandis* and understorey of wet sclerophyll and young rainforest trees.

south coast shrublands of the Fitzgerald River region, western Australia, where Roe (1849; cited in Hassell and Dodson 2003, 82) described dense, unburned shrubland areas shunned by the Aboriginals. Hassell and Dodson (2003) concluded that pre-settlement Aboriginal population densities had direct implications for the extent and intensity of burning.

Overall, this suggests that frequent Aboriginal burning may have been a feature of some parts of the landscape but not others. According to Hassell and Dodson (2003), there is a strong correlation between resource richness (access to fresh water, and moderate to high soil fertility – such as on alluvial soils of river valleys), Aboriginal population sizes at the time of European settlement, and the frequency of vegetation treatment by fire. Some forests with an open and grassy understorey may have been natural, while others were maintained through the managed use of fire. Other forested areas had dense, shrubby understoreys and may have experienced

Fig. 4. Dry sclerophyll forest near Perth, southwestern Australia, dominated by the fire-tolerant jarrah (*Eucalyptus marginata*), with banksia (*Banksia grandis*) and grasstrees (*Xanthorrhoea preisii*) in the understorey.

Fig. 5. Mature (15 years since last fire), high-diversity Mediterranean-type shrublands near Eneabba, western Australia, rich in shrub species from the families Proteaceae and Myrtaceae.

fire regimes similar to those of today (see Table 1). Shrublands too may have been largely unmanaged, reflecting their low resource quality (for people) relative to other parts of the landscape. Gill and Catling (2002) concluded that reconstructing mean fire frequencies (and their ecological consequences) for forested areas of southern Australia from historical records is fraught with difficulty and has met with little success.

Table 1. Generalised relationships between vegetation type, annual rainfall (mm), fuel load (surface and near-ground live fuels), estimated 'natural' (i.e. primarily lightning ignition) fire interval, level of use of managed fire by Aboriginal peoples in the pre-European period, and level of resources (water, plants, animals) to support indigenous populations for major ecosystem types in Australia.

Vegetation type	Annual rainfall[3]	Fuel load	Natural fire interval	Managed fire interval	Resource level
Tropical rainforest	>1600	Moderate	Very long (>300 years)	N/A; except ecotone with savanna	High
Tropical savanna	500–1600	High	Very short (2–4 years)	Very short (1–3 years)	Moderate
Semi-arid spinifex grasslands	250–500	Low to high	Intermediate – long (10–30 years): rainfall-spinifex biomass event driven	Short (3–10 years); spinifex areas treated when possible	Low; but occasionally high
Desert	<300	Low	Long (20–50 years): rainfall-annual grass biomass event driven	Intermittent; not actively managed with fire	Low
Shrubland	300–600	Moderate	Short – intermediate (10–30 years)	Intermittent; not actively managed with fire	Low
Dry sclerophyll forest[1]	600–1200	Low	Intermediate – long (30–100 years)	Intermittent; not actively managed	Low – moderate
Dry sclerophyll forest[2]	400–600	Moderate to high	Intermediate (10–20 years) and long (50–80 years)[4]	Short (2–5 years), understorey only	Moderate
Wet sclerophyll forest	1000–1600	High	Intermediate (10–30 years) and long (50–100 years)	Intermittent (6–10 years); mainly ecotones	Low – moderate
Temperate rainforest	>1600	High	Very long (>300 years)	N/A; except ecotone with moorlands	Low – moderate

Data for fuel loads and fire intervals are based on accounts in Gill et al. (1981), Bradstock et al. (2002), and other sources.

[1] Dry *Eucalyptus* forests with moderate to high rates of litter and near surface live fuel accumulation; for example, the stringybark (*E. macrorycha*) forests of southeastern Australia and jarrah (*E. marginata*) forests of southwestern Australia.

[2] Dry *Eucalyptus* forests with low rates of litter and near surface live fuel accumulation; for example, the Box-Ironbark (*E. tricarpa*) forests of southeastern Australia and salmon gum (*E. salmonophloea*) forests of southwestern Australia.

[3] The range of annual rainfalls associated with different vegetation types is shown. Ranges are overlapping, reflecting variations in the relationship between rainfall and vegetation associated with local factors, including altitude, aspect, geology and drainage.

[4] Fire history reconstructions for these forest types indicate more frequent low-severity understorey fires as well as longer-interval high-severity fires (stem-scarring in dry forests, stand replacing in wet forests).

Fig. 6. A button-grass (*Gymnoschoenus sphaerocephalus*) moorland/temperate rainforest ecotone, central Tasmania.

Fig. 7. Dry season (winter) surface fire in *Eucalyptus*-dominated tropical woodland savanna, northeastern Queensland.

Information on fire size is difficult to ascertain from historical accounts and is less amenable to quantitative analysis. Many early accounts refer to multiple ignitions (or smoke plumes) being observed on the same day, indicative of small individual size (Abbott 2003), and some note the approximate length of burned areas traversed on particular journeys. These range from less than 1 km, to many tens of kilometres. Very large fires are also recorded. Sources as early as Vlamingh (for western Australia in 1697) describe apparently extensive fires visible from sea (Abbott 2003), while Gill (2000) reports historical accounts of fires in central Australia being lit in hot, windy conditions conducive to rapid fire spread, and ultimately covering tens of thousands of hectares.

Burrows and Christensen (1990) analysed fire scars from 1953 air photos covering an area in the Western Desert of western Australia, revealing a mosaic of 372 scars with mean size of just 34 hectares. They contrasted this with a later (1986) satellite image analysis for the same area showing a single fire scar of 32,000 hectares. The depopulation of Aboriginal peoples in the intervening period is argued as a possible explanation for this apparent change in fire size, replacing a fine-grained mosaic of different aged vegetation patches with a uniform vegetation resulting from large, lightning-caused fires (Bowman 2003). However, large fires are more likely in these desert systems following years of high rainfall that produce a rapid accumulation of grassy fuels capable of carrying high-intensity fires if an ignition occurs, so that even under indigenous stewardship, periods characterised by small mean fire size (under low fuel continuity and biomass conditions) may have been interspersed with occasional large fires. Haydon et al. (2000) analysed spinifex hummock grasslands of the Great Victoria Desert for the period 1972–1991 using satellite imagery, and estimated mean fire size as 2800 hectares – values intermediate between those reported for 1953 and 1986 by Burrows and Christensen (1990) – with a return interval of 20 years.

We can conclude that many fires were small, while some were large – but can say little about absolute sizes and size frequency distributions. Fires in open, grassy areas were likely to be frequent (every few years), while many other areas were heavily wooded and may have experienced fire less frequently.

Scientific Investigations of Fire Interval

Most sources of evidence based on scientific investigations of fire regimes in Australian vegetation suggest much longer intervals between crown fires in the pre-European period than surmised above (Table 1). In western Tasmania, Jackson (1965, 1968) and Bowman and Jackson (1981) describe succession from wet sclerophyll forests with a fire-sensitive *Eucalyptus* spp. overstorey (developed over fire-free intervals of 80–150 years) to temperate rainforest dominated by *Nothofagus cunninghamii* where fire intervals exceed 200 years. Wet scrub comprised of shrub species from the Myrtaceae and Ericaceae (among others) forms an intermediary between *Eucalyptus* forests and moorland in areas exposed to more frequent fire, while the most frequently burnt areas support Buttongrass Moorland dominated by the sedge, *Gymnoschoenus sphaerocephalus* (Figure 6). Ecological (Mount 1982) and palaeo-ecological investigations across Tasmania support, in a general sense, this succession determined by fire regime (Colhoun 2000; Fletcher and Thomas 2007; MacPhail 1975; MacPhail and Colhoun 1985; Markgraf et al. 1986; Thomas 1994), and suggest that since the Last

Glacial Maximum, the basic distribution and composition of major plant communities here has remained rather stable.

Using tree-ring evidence, Banks (1988) reports infrequent fire (one to two large fires per century) in Snow Gum (*Eucalyptus pauciflora*) woodlands near tree line in the Australian Alps prior to European settlement, followed by a sudden increase in the frequency of fire after the introduction of European settlers and their livestock to the alpine and sub-alpine areas of southeastern Australia. Mackey et al. (2002) identified a stand-killing fire interval of 75–150 years for Mountain Ash (*Eucalyptus regnans*) wet sclerophyll forests of northeastern Victoria based on stand age structures (Figure 3), while Burrows et al. (1995) reported a mean fire interval of about 80 years for tree-scarring fires in jarrah (*Eucalyptus marginata*) forests of southwestern Australia (Figure 4) in the pre-European period.

In temperate woodlands of southwestern Australia, Hobbs (2002) argues that the available evidence supports the notion of a change from less frequent (40–50 years) to more frequent (6–8 years) fire following European settlement. Enright et al. (1996, 1998) and Groeneveld et al. (2002) investigated the demography of *Banksia* species in fire-prone shrublands of the Eneabba sandplain (Figure 5), finding that fire intervals <8 years would threaten fire-killed species with local extinction. Keith et al. (2002) reported minimum fire recurrence intervals of 5–8 years for Australian shrublands based on fuel accumulation rates, while in drier vegetation assemblages of southern Australia such as mallee (small, multi-stemmed fire-tolerant *Eucalyptus* species), slow fuel accumulation rates preclude the recurrence of fire within 7–10 years of previous fire (Cheal et al. 1979; Noble 1984).

In relation to forested sites, Bowman (1998) warns that the dendrochronological (tree-ring) record for fire does not necessarily register low-intensity fires that fail to damage the cambium layer of trees, and so may exclude Aboriginal burning of the understorey. While true, this argument would also indicate that frequent understorey burning failed to preclude tree-scarring, high-intensity fires from recurring at the intervals indicated by the tree-ring and other records described above. Furthermore, the age structure of many present-day stands of fire-sensitive Mountain (*Eucalyptus regnans*) and Alpine Ash (*Eucalyptus delegatensis*) wet sclerophyll forest in southeastern Australia reflects a pre-European history of stand-killing, high-intensity fires. Such fires are important for recruitment of the species and for the provision of tree hollow-nesting sites for birds and small marsupials (Lindenmayer and Possingham 1995).

Small patch burning is also likely to have proven difficult in closed forests on moist south-facing slopes and valleys in mountainous areas of southeastern Australia – as it is today. Such areas are only likely to burn under extreme weather conditions, and then bushfires will quickly spread through areas even if they were burned only a few years earlier (McCarthy and Tolhurst 2001). Simulation modelling based on different scenarios concerning ignition sources and frequencies, and vegetation and fire spread properties, further informs the debate concerning past landscape patterns, particularly in relation to fire size and habitat heterogeneity. For example, Piñol et al. (2007) modelled fire spread in Mediterranean-type vegetation based on data for the Mediterranean Basin and California, finding that fuel reduction through managed fire (i.e. frequent ignitions) reduced the average fire size, but that large fires still occurred (regardless of fuel age) under extreme weather conditions. On the other hand, according to Thomas (1994), the apparently stable distribution of fire-prone moorlands in high rainfall areas of western Tasmania, may result from a long history of people propagating fire in the landscape, with a developing inertia to change in the absence of fire where poor drainage and peaty deposits have become established.

A recently developed technique for reconstructing past fire intervals based on visible colour banding of leaf bases on the stems of grasstrees (*Xanthorrhoea preissii*) – in a method analogous to (but much less precise than) tree-ring reconstructions – has been reported by Ward et al. (2001) and Lamont et al. (2003). They present a fire history record for sclerophyll (*Eucalyptus*) forests and shrublands of southwestern Australia with fire intervals for the period from 1750 to 1930 much shorter than at present; averaging only 3–5 years, arguing that it represents the pre-European burning regime practised by Aboriginal peoples. After 1930, they report less frequent fire, with intervals between fires similar to those based on field observations and documentary records over the past 30–40 years (i.e. fire intervals of 10–15 years).

These findings have added a direct source of evidence previously lacking in relation to the pre-European fire regime debate. If the grasstree record is valid, then the structure and composition of Australian plant communities where such fire regimes occurred may have been markedly different in the recent past from that observed today, and in the period prior to human presence in Australia. However, it is unclear how fire-killed woody plants with juvenile stages of ~3–5 years could have survived such a fire regime. Currently, the grasstree record is based on only a small number of records and does not yet provide any evidence concerning the scale of burning that may have occurred in these vegetation types. The records indicate that, prior to 1930, almost all individual grasstrees were burned every 3–5 years, so that even if fires were small and patchy, all patches were burned within a few years. Enright et al. (2005, 2006) and Miller et al. (2007) have reported on inconsistencies in grasstree fire history records from high-diversity shrublands in western Australia and have suggested caution in interpretation of this fire history until further verification studies have been completed. Burrows and Wardell-Johnson (2003) urged caution also in generalising the grasstree record to other vegetation types where grasstrees are absent or have not been sampled.

In relation to the demography of woody species in fire-prone vegetation, it is equally difficult to explain how the many resprouter species that are now widely distributed across the landscape could have established mature populations so broadly under a frequent fire scenario given limited seed production (low colonisation ability) and poor seedling survival if affected by fire when very young. For example, Enright and Lamont (1992) estimated that mature individuals of the abundant resprouter species, *Banksia attenuata*, in the Eneabba sandplain shrublands of western Australia may live for up to 300 years. Their secondary juvenile stage lasts 2 years, so that no seed is likely to be available until at least 3 years after any fire, and seed store would be low for several years after that. Those very few seedlings recruited after fires at 3- to 5-year intervals would then be subjected to fire again at age 3–5 years, with the probability of surviving fire increasing with age. Modelling studies taking all of these life history and fire regime factors into account (Groeneveld et al. 2002) found that populations of *Banksia attenuata* would slowly decline for fire intervals of less than 8–10 years. Similarly, Burrows and Wardell-Johnson (2003) note that, although many understorey species of jarrah (*Eucalyptus marginata*) dry sclerophyll forest commence flowering within 2–3 years of fire, accumulation of a sufficient seed store to ensure parent replacement after fire is likely to require at least twice this period, coinciding more closely with fuel-based estimates of understorey fire risk (low-intensity fires at 5- to 8-year intervals) than with the 2- to 5-year intervals reported for the pre-European period.

In the Sydney region, Mooney et al. (2007) and Black et al. (2006, 2007) sought explicitly to identify the relationship between fire, climate and people in the pre-European period through pollen and charcoal analysis of lake and swamp sediments. They report relatively stable *Casuarina*-dominated woodlands from 43 ka BP to around 10 ka BP, suggesting resilience to climate changes and little impact from fire despite the likely presence of people (Black et al. 2006). At one site, a substantial increase in fire is recorded after 3 ka BP along with changes in archaeological evidence for increased human activity in the area, with an increase in fire frequency to around eight events per century (Mooney et al. 2007). However, whether these changes represent climate impacts associated with increased ENSO intensity, modified human use of fire in response to this greater climate variability, or a combination of the two, remains uncertain (Black et al. 2007).

NORTHERN (TROPICAL) AUSTRALIA

In northern Australia, lightning strikes and anthropogenic fire together play a crucial role in determining the composition and distribution of plant and animal communities. The vast savanna woodlands that extend from the Indian to the Pacific Ocean across more than 3000 km of undulating plateau, dissected ranges and alluvial plains are maintained by fire (Figures 1 and 7). In contrast, the distributions of isolated pockets of fire-sensitive rainforest and more extensive rainforests along the Queensland coast are, to a large extent, maintained through the absence of fire (Bowman 1998). Northern Australia is strongly dominated by the tropical monsoon. In Kakadu National Park (Northern Territory), an annual rainfall of 1200 mm falls during a 6-month 'wet' season (November to April), with fires becoming more common and severe towards the end of the 'dry' season as temperature increases and humidity decreases, causing grassy fuels to cure (Gill et al. 1996). The frequent occurrence of pre-monsoonal lightning strikes causes hundreds of fires every year. Added to this are many more fires lit by people.

Much of northern Australia has been settled by Europeans for only about 100 years, although some early historical comments on fire are recorded in the accounts of 19th-century explorers; for example, Leichardt noted that savanna grassland surrounding the Gulf of Carpentaria was burned much more frequently than either coastal forests or semi-arid grasslands (see Crowley and Garnett 2000; Fensham 1997). Furthermore, there appear to have been deliberate strategies to set fires in autumn and winter (early to mid-dry season), rather than in late spring or summer (Fensham 1997). In the Kimberly region, an analysis of explorer accounts indicates that fires were common in winter (mid-dry season) but that spring (late dry season), and even some early summer fires (wet season), were also lit by Aborigines (Vigilante et al. 2004). An analysis of 25 available Northern Territory explorer accounts by Preece (2002) provides over 150 references to landscape-scale fires. There is apparent concordance across the historical evidence in regard to seasonality and frequency of landscape fires: burning commenced during the early dry season and continued intermittently until the beginning of the wet season when burning ceased. These findings appear to hold for almost all of the tropical savanna and even into the pastoral lands of Cape York Peninsula (Crowley and Garnett 2000). The overall pattern is one of return intervals for fire of around 2 years under higher and more reliable rainfall in the tropical woodland–savanna areas, declining to intervals of 5 or more years under lower and less reliable rainfall further south (Felderhof and Gillieson 2006). In the latter case, large fires are most commonly associated with greater grassy fuel loads that develop in response to above average rainfall in the previous year, as described also by Luke and McAthur (1978).

Many Aborigines still use fire as a management tool on traditional lands in northern Australia and can attest to fire knowledge passed on to them by older relatives or clan members. As late as the early 1960s, some Aboriginal peoples lived a life almost totally isolated from European settler influences, and in this sense, the short European historical record overlaps with contemporary and pre-European indigenous life and history, so that knowledge of the customary use of fire is better here than anywhere else on the continent. The testimony from living Aborigines concerning their use of fire is voluminous (Langton 1998, 2000; Lewis 1989). Equally significant are the contributions of an increasing number of indigenous scholars (Hill et al. 1999; Langton 1998, 2000; Whitehead et al. 2003); for example, in a study combining scientific investigation of fire and biological resources with ethnographic observations in a clan estate (Dukaladjarranj) near Kakadu National Park, Yibarbuk et al. (2001) found that burnt areas attracted large macropods and had little impact on fire-sensitive vegetation. They concluded that the customary practice of lighting small, manageable fires in co-operation with clan members, acted to maintain diversity across all structural types of vegetation and landscapes, with conservation of biodiversity not incompatible with customary fire management for ritual and economic reasons.

The palaeo-environmental record for climate, vegetation and fire in tropical Australia was, for a long time, based on data from a few terrestrial sites on the Atherton Tablelands of northeastern Queensland near Cairns (especially Lynches Crater; Kershaw 1974; Kershaw et al. 1993). More recently, a mix of long, marine core records, including ODP-820 in the northeast (Kershaw et al. 2002; Moss and Kershaw 2007) and GC-17 in the northwest (van der Kaars and De Deckker 2002), and short terrestrial cores (e.g. Rowe 2007) have added considerable detail to this record. Increases in carbonised particles occur in both terrestrial peats and marine sediments in the northeastern Queensland region around 45–38 ka BP (Turney et al. 2001) and are accompanied by major plant community changes, the most significant being the almost total elimination of dry rainforests with Araucariaceae as a dominant and it is replacement by sclerophyll (*Eucalyptus* dominated) forest. Initially, it was thought that this sudden increase in charcoal (fire) and decline of dry rainforest taxa marked the entry of Aboriginal peoples into the continent and reflected a regional signal of anthropogenic fire (Kershaw 1986). However, the influence of climate shifts, including the intensification of ENSO (Lynch et al. 2007), may also be involved in the increase in fire after this time.

Late Holocene dates from charcoal in soil pits from many lowland rainforest plant communities indicate a much more dynamic relationship between rainforest and sclerophyll forest than previously thought. The data indicate the former presence of sclerophyll pyrophytic communities and a subsequent expansion of lowland tropical rainforest (Hopkins et al. 1996). The wet tropical forests prominent today in the region are relatively recent communities that expanded rapidly again between 12–7 ka BP regardless of the presence of people and fire (Moss and Kershaw 2000). Other evidence for relatively recent shifts in community composition comes from the distribution of avian megapod nesting mounds (Bowman et al. 1999). The orange-footed scrub turkey builds large nesting mounds in rainforest from leaf litter and soil. The birds are restricted to rainforest and yet the remains of unattended mounds can often be seen in adjacent sclerophyll woodland. This distribution clearly signals a local retraction of rainforest and a commensurate build up of flammable sclerophyllous litter.

Ecological research in the wet tropics of northeastern Queensland has determined that, to a large extent, the location of sharp ecotones between tropical rainforest and sclerophyll vegetation is controlled by fire (Ash 1988). In the homelands of the Kuku-Yalanji people near Mossman, north of Cairns (Hill et al. 2000), burning of flammable sclerophyll forests by traditional owners, did not preclude the persistence of extensive rainforest cover in close association with it. Even in dry, fire-prone areas such as the Arnhem Land escarpment, many pockets of fire-sensitive 'dry rainforest' persist in locations without topographical protection from fire. These may reflect a conservative system of indigenous fire management (Bowman 1998), although rainforest boundary expansion in Kakadu since the 1960s indicates that current fire regimes are not a major threat to rainforests that may be spreading in response to global climate change factors (Banfai et al. 2007).

In the savanna woodlands of the Northern Territory, a large, landscape-scale manipulative fire experiment at Munmarlary (Kakadu) showed little change in response to differing intensity and season of fire over a 13-year period (Bowman et al. 1988; Lonsdale and Braithwaite 1991). Neither grass nor woody species cover displayed any systematic response to any treatment other than fire exclusion, which resulted in increased shrub density. It was concluded that subtle edaphic differences were responsible for determining vegetation patterns and that fire was so common and had such a long history, that intensity and seasonality made little practical difference at all. A re-analysis of the results some years later (Bowman and Panton 1995) reaffirmed these conclusions.

A second, much larger series of experiments at Kapalga (Kakadu) between 1990 and 1994 (Andersen et al. 1998, 2005; Williams et al. 2003a,b) utilised land units of 15–20 km^2 in which compartments were burned according to one of four treatments: early dry season, late dry season, progressive through the dry season, and unburnt controls, with each treatment replicated at least three times (Andersen et al. 1998). The effects of treatments were assessed for invertebrates, reptiles, tree mortality and survival, seed production and other environmental variables with results broadly commensurate with those found by the Munmarlary experiment. Little change occurred in the vegetation regardless of fire season and intensity. Early-season, low-intensity fires had no significant effect on tree mortality but there were losses in overall biodiversity. Late dry-season fires had a significant effect on tree mortality with up to 20% of stems dying in some treatments but with little or no change to biodiversity (Williams et al. 2003a). Progressive dry-season fires had no unique results, while unburnt areas tended to accumulate fuel loads that may ultimately prove problematic because fuel loads build up quickly over 2–4 years, supporting lightning ignition fires at this frequency.

The muted response by savanna plant communities to fire suggests a high degree of resilience to any impacts on biodiversity from customary burning by Aboriginal peoples over thousands of years (Andersen et al. 1998). Overall, the multiple lines of evidence suggest that, compared to the pre-human fire regime, pre-European (Aboriginal) fires were probably more frequent and smaller, while evidence for shifts in season of fire to the early dry season is somewhat equivocal. Rather than a shift in season, it is possible that the fire season was broadened, with fires lit early, mid- and late dry season in different habitats and for different reasons.

Compared to pre-European fire, modern fires are more frequent again, and are larger, while shifts in season of fire are again unclear, varying geographically in relation to habitat and land management. For example, Bowman et al. (2004) utilised Landsat images to map vegetation changes over a decade in an 8000-km^2 area in Arnhem Land that included several Aboriginal settlements. Fires were found to be generally of low intensity but were lit mostly in the latter part of the dry season. However, in another study, Bowman et al. (2007) report that carbon particulate change at Darwin since the 1950s suggests a shift to more fire early in the dry season with the change from Aboriginal to European land management.

Consistent with findings from southern Australia, fire interval in rocky upland and plateau areas was not only lower than in savannas, reflecting less continuous fuel loads, but also lower resource availability and resource response to fire (Murphy and Bowman 2007). Biodiversity in these areas is susceptible to significant impacts from increased fire frequency, with fire-sensitive species most at risk (Russell-Smith et al. 2002).

Synthesis

The analysis presented here seeks neither to discredit nor to promote the notion of 'stewardship by fire' of the Australian landscape by Aboriginal peoples during their period of unique tenure, but to provide a balanced position from which we may reasonably conclude how best to advance the managed use of fire for the conservation of the species and habitats that remain in our care. This is especially complex given the need to meet the multiple objectives of competing interest groups in our society.

Aboriginal burning was, and still is, purposeful – it had objectives that included the optimisation of food resources (either through hunting or direct growth of plant products), the removal of dense understorey to facilitate easy travel, and asset protection (e.g. of human life, and of fire-sensitive sites of cultural and resource significance). In most of tropical and arid Australia, knowledge of traditional burning objectives and strategies remains extant, and important for land management. The high frequency of lightning, and natural patterns of build-up of grassy fuel loads, suggests that the addition of a human ignition source may not have altered greatly the structure and composition of savanna ecosystems, even though there may have been some increase in fire frequency, a decrease in mean fire size, and shifts in fire season. However, evidence for possible tree recruitment failure in response to post-European increases in fire frequency in some areas, and monsoon forest expansion in others, shows that the tree–grass balance is sensitive to fire regime change under current climate and may have shifted in response to pre-European fire regime changes. Further palaeo-environmental research may answer this question.

In temperate Australia, information on pre-European fire regimes is fragmentary, and relies heavily on palaeo-environmental reconstructions based on pollen and charcoal, and on scientific evidence concerning fire behaviour and its ecological effects on these, often highly flammable, ecosystems. The fire regimes of vegetation types, including shrublands, low fuel load rangelands and wet forests, may have remained largely unaltered by people in the pre-European period. In contrast, the extensive dry sclerophyll (mostly *Eucalyptus* dominated) forests and woodlands characterised by higher fuel loads were likely more actively (and frequently) 'treated' with fire. However, large, high-severity fires still occurred from time to time. While there were major impacts on megafauna following the arrival of people in Australia, and this hints at possible shifts in the nature of plant resources available to them (or affected by them), there is little direct evidence of major shifts in the abundance or distribution of plant species and communities as a result of changes in fire regime. Furthermore, the explicit role of pre-European (Aboriginal) fire regimes in the conservation of species and populations of plants and animals also remains unclear. Other cultural practices designed to preserve species of significance may have been more important and these may have intersected with how fire was managed. While many animal and plant species were, and are, known by name and are assigned significance, it is not clear that all species (e.g. those with no resource or totem value) were valued and managed equally. As with current philosophies of species conservation management, strategies that seek to ensure the survival of key species might or might not adequately protect other species for which data are lacking.

In relation to modern fire management, we must ask whether there might be conflicts between the cultural and resource exploitation goals of Aboriginal burning and the species conservation (and other) goals of management in parks, reserves and public estate lands (Langton 1998). The objectives of fire management today include fuel load reduction to assist in asset (human life and property) protection, and fire season, interval and intensity management to maintain native plant and animal species populations, to safeguard fire-sensitive habitats, and to reduce the negative impacts of invasive species. The massive number of plant and animal introductions that has accompanied European settlement of Australia means that few if any ecosystems will necessarily respond to fire in the way that they may have in the pre-European past (Werner 2005). For example, modern fire regimes may favour the survival and expansion of invasive animals and plants, such as blackberry (*Rubus* spp.) in southern temperate forests, buffel grass (*Cenchrus ciliatus*) in some arid zone areas, and gamba grass (*Andropogon gayanus*) in northern Australian savannas. In the case of the latter, a major shift in fire regime to frequent, high-intensity fires associated with increased fuel loads has the potential to significantly alter vegetation structure and composition, highlighting new demands on managed fire as a means of minimising exotic species impacts (Rossiter et al. 2003). Small patch size of fires has also been found to result in higher rates of insect and mammal granivory and herbivory than occur for large fire sizes, so that species composition and abundance relationships can also be affected (Cowling and Lamont 1987).

It is our view that not enough is known about traditional Aboriginal burning strategies and objectives in temperate Australia to be able to re-create an Aboriginal fire management regime or to know its potential consequences. Knowledge has been lost due to the alienation of tribes from their land, or is fragmentary. In northern and central Australia, traditional knowledge remains extant; tens of thousands of indigenous people speak their own language and deal with fire as an ongoing tradition. While it would be advantageous to have Aboriginal knowledge added to the decision-making process – as is now done for Kakadu and Uluru-Kata Tjuta National Parks in the Northern Territory (Langton 2000) – any use of a 'traditional Aboriginal burning regime' on public estate lands in southern Australia would be an experiment in land management, rather than a re-creation of Aboriginal fire regimes, and should be recognised as such. The overall weight of evidence suggests that smaller, lower-intensity fires were more common in many Australian ecosystems prior to European settlement of the continent, and that their administration was not necessarily deleterious to biodiversity values. Recent reports of inquiries into the extensive unplanned fires that have affected southeastern Australia in the past decade recommend an increase in the total area burned per year by planned fire to reduce the risk of large, high-intensity wildfires. However, any increase in the area burned, and decrease in fire interval associated with such a strategy, will need to remain based on scientific criteria that seek to meet current (and evolving) biological conservation and asset protection objectives rather than being based in any sense on uncertain past regimes.

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