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The impact of Aboriginal landscape burning on the Australian biota

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CONTENTS

SUMMARY

One of the most complex and contentious issues in Australian ecology concerns the environmental impact of Aboriginal landscape burning. This issue is not only important for the development of a comprehensive understanding of the dynamics and evolution of the Australian biota, but is central to the formulation of appropriate strategies for the conservation of the nation's biodiversity. Ethnographic evidence leaves little doubt that Aboriginal burning played a central role in the maintenance of the landscapes subsequently colonized by Europeans. Both 19th century European colonists and anthropologists in the 20th century documented the indispensability of fire as a tool in traditional Aboriginal economies, which have aptly been described as 'fire-stick farming'. Aborigines used fire to achieve short-term outcomes such as providing favourable habitats for herbivores or increasing the local abundance of food plants, but it is not clear whether or not Aborigines had a predictive ecological knowledge of the long-term consequences of their use of fire. A large body of ecological evidence suggests that Aboriginal burning resulted in substantial changes in the geographic range and demographic structure of many vegetation types. Aboriginal burning was important in creating habitat mosaics that favoured the abundance of some mammal species and in the maintenance of infrequently burnt habitats upon which the survival of specialized fauna depends. Aboriginal fire regimes were probably critical for the maintenance of at least one species of tree (*Callitris intratropica*) in the monsoon tropics.

The question of the original impact of humans on the Australian environment is fundamentally speculative because of vague, disputed time frames proposed for the waves of colonization and shifting settlement patterns of

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Aborigines in the late Quaternary period. There is an inherent circular argument concerning the cause and effect of climate change, vegetation change, and burning through the late Quaternary. Charcoal and pollen evidence from long sedimentary cores is ambiguous and cannot be used to demonstrate unequivocally the initial impact of Aboriginal people on the landscapes of Pleistocene Australia. The sparse available evidence does not support the hypotheses that Aboriginal burning was primarily responsible for the extinction of Pleistocene megafauna; was critical for the maintenance of habitats of small mammals that have become extinct following European colonization; initiated widespread accelerated soil erosion rates in either the Pleistocene or Holocene; or forced the evolutionary diversification of the Australian biota. Burning may have caused the extinction of some fire-sensitive species of plants and animals dependent upon infrequently burnt habitats, and it must have maintained structurally open vegetation such as grasslands and also extended the range of fire-adapted species, such as *Eucalyptus*, into environments climatically suitable for rain forest. Palaeoecological research concerning prior impacts of Aborigines must give way to focused studies of the role of different anthropogenic fire regimes in contemporary ecosystems that have not been destroyed by European colonization. Such research is crucial for comprehending the role of Aboriginal burning in the maintenance of Australia's unique, rich biodiversity.

Key words: Australia, ethnoecology, fire ecology, history of vegetation, landscape ecology, palaeoecology.

I. INTRODUCTION

The role of Aboriginal landscape burning in moulding the Australian biota is a complex and intellectually vexatious issue. A simple caricature of this debate asks how the biological 'furniture' of the Australian landscape was rearranged by Aboriginal burning in the recent and distant past. Some scholars regard the effect of Aboriginal burning as 'trifling' (Cleland, 1940) and consider that Aboriginal people are part of the Australian biological furniture (Cleland, 1940, 1957; Horton, 1982). Other scholars have suggested that Aborigines used fire to rearrange the biological furniture to suit their needs (Gott, 1982; Hynes & Chase, 1982), especially by employing 'fire-stick farming' (Jones, 1969). A far more extreme view, which is currently ascendant in scholarly and popular discourse, is that the Aborigines were 'pyromaniacs' (Merrilees, 1968) who initially burnt the biological furniture and then had to learn to live with the consequences of their destructive actions (Tindale, 1959; Merrilees, 1968; Janzen, 1988; Flannery, 1990*a*, 1994; Latz, 1995).

The question of Aboriginal burning is important to a large number of academic disciplines, most of which have just one thing in common: the landscapes of Australia. The interchange of ideas between disciplines has been *ad hoc* with signs of intellectual hegemony. For example, the archaeologist Bowdler (1990) expressed annoyance that the alleged environmental impact of prehistoric Aborigines has become a 'panacea' for other palaeoecological disciplines to solve otherwise intractable problems. Nonetheless, archaeologists must accept that a complete appreciation of Australian ecosystems requires serious thought concerning Aboriginal burning (Flannery, 1990*b*). Some ecologists have argued that because there is so much uncertainty concerning the use of fire by Aborigines, the whole topic is best side-stepped and the functioning and management of fire-prone ecosystems should be worked out by standard ecological methodologies (Gill, 1977). The knowledge and opinions of Aborigines have been rarely heard or recorded in this debate. Fortunately some social scientists (Lewis, 1989; Rose, 1995, 1996), ecologists (Haynes, 1978; Russell-Smith *et al.*, 1997) and Aboriginal scholars (Langton, 1998) are now beginning to redress this omission.

Debates concerning Aboriginal burning have not remained solely academic. With the recent, legal recognition of the original occupation of Australia by Aborigines, the debate concerning deliberate modification of the Australian environment with fire has shifted into the legal sphere (Hughes, 1995). Numerous books about Aboriginal burning underline the profound importance of this debate to Australians (Blainey, 1975; Lines, 1991; Pyne, 1991; Flannery, 1994; Kohen, 1995; Latz, 1995). Uncontrolled landscape fires, known in Australia as 'bushfires', have recurrently caused the loss of life and property on the fringe of many Australian cities (Gill, 1981). These disasters often colour debates about landscape burning.

Given this complex intellectual setting it is naive to assume that yet another review can resolve this debate. It is more likely that the various strands can be made into a rope strong enough to snare excessively speculative arguments. This is my aim. I will first consider what is known about Aboriginal landscape burning and review evidence that burning was an ecologically significant factor. I then consider the prehistoric record and several palaeoecological arguments that emphasize the destructive role of Aboriginal burning. Finally, I suggest possible avenues for future research.

II. ABORIGINES AND FIRE

1. *Ethnohistorical evidence: stories and text*

For some scholars the writings of 18th and 19th century explorers and settlers are too unreliable a record of Aboriginal landscape burning practices

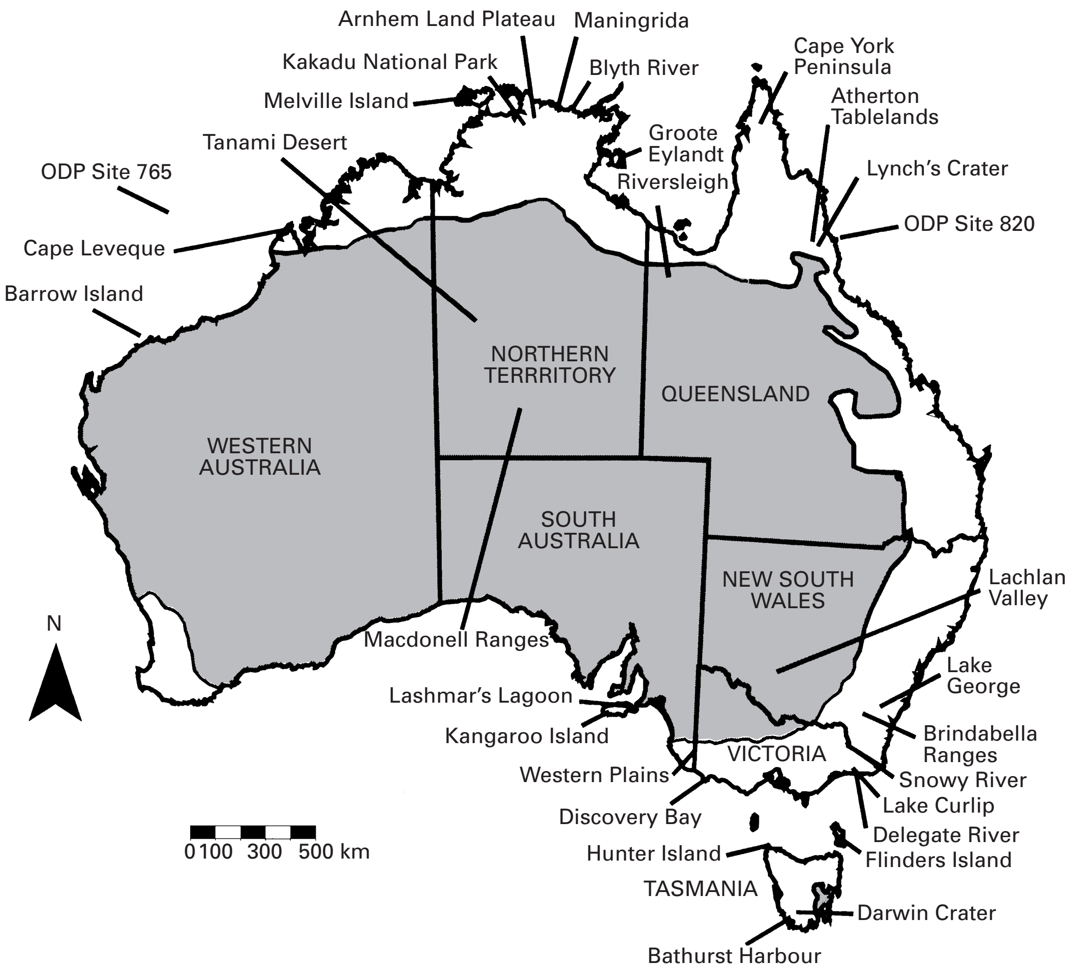

Figure 1. Location of various Australian and Tasmanian sites relating to the study of Aboriginal landscape burning. Land that receives < 600 mm annual rainfall is shaded.

and are considered best ignored (Gill, 1977; Horton, 1982). Concerns about the validity of the ethnohistorical record focus on the biases and reliability of the explorers and their unquantifiable effects upon the Aboriginal behaviour. Selective use of historical sources by scholars has also resulted in disagreements as to the ecological significance of burning (Benson & Redpath, 1997). The fires so many explorers saw may have been a hostile or terrified response to strange white people invading tribal lands (Fensham, 1997). Furthermore, the explorers may have exaggerated the amount of burning they reported because of their own fears and alienation (McBryde & Nicholson, 1978). However, the ethnographic record, although constrained by limitations of reliability, reveals more than the minimal fact accepted by Horton (1982) that 'fires were occurring in Australia during the early days of white settlement' (Hiatt, 1968; Nicholson, 1981; Horton, 1982; Kimber, 1983; Bowman & Brown, 1986; Fensham, 1997). Aborigines in the 19th century burned landscapes for a great variety of purposes such as clearing thick vegetation to facilitate travel, signalling, controlling insects and vermin, hunting and waging war (King, 1963; Hiatt, 1968; Jones, 1969; Hallam, 1975, 1985; Stockton, 1982; Kimber, 1983).

Compilation and analysis of records has provided insight into the variation of landscape fire in space and time (Hallam, 1975, 1985; Stockton, 1982; Kimber, 1983; Bowman & Brown, 1986; Braithwaite, 1991; Fensham, 1997). For example, in the most rigorous analysis of 19th century explorers' journals, Fensham (1997) showed that landscape fires in Queensland were most common in winter and autumn, and that the frequency of fires was much higher in coastal and sub-coastal areas than inland areas (Figs 1, 2). Weaknesses in the record include an inability to determine accurately the spatial extent of fires, the different types of vegetation burnt and the reasons why fires were lit (Hiatt, 1968; Horton, 1982; Bowman & Brown, 1986; Fensham, 1997).

Perhaps the greatest problem with the historical record concerns its inability to answer the question of whether or not Aborigines had a predictive knowledge of the ecological consequences of burning, and especially long-term outcomes (e.g. Latz & Griffin, 1978; Nicholson, 1981; Hallam, 1985; Fensham, 1997). Some explorers concluded that

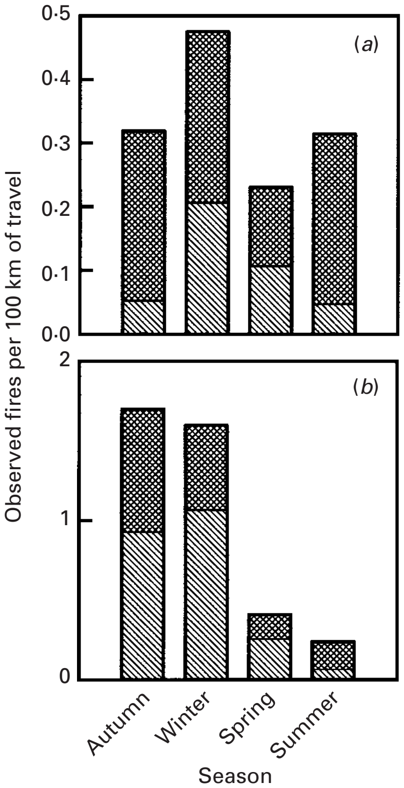

Figure 2. Numerical analysis of records of Aboriginal burning derived from the journals of 19th century explorers in Queensland (Fig. 1) (*a*) Inland; (*b*) coastal and subcoastal. ▧, Past fires; ⊠, current fires. This shows the number of records of fires in the landscape ('current fires'), which may have been lit in response to the presence of the explorers, and records of recently burnt landscapes ('past fires'), which would not have been influenced by the presence of the explorers. The records are standardized by expressing records for 100-km sections of each explorer's traverse and are broken down by season: summer, December to February; autumn, March to May; winter, June to August; and Spring, September to November. The 'inland' and 'coastal and subcoastal' categories includes the following communities: 'Inland' – Aristida, Channel, Spinifex, Brigalow, Blue grass; 'Coastal and subcoastal' – Blady grass, Blue-grass-brown top, littoral, rainforest, Blackspear grass and Schizachyrium (adapted from Fensham, 1997). In Queensland rainfall occurs throughout the year. For inland regions rainfall is low ($<$ 600 mm yr^{-1}) and erratic while in coastal regions annual rainfall exceeds 2000 mm. Summer rainfall increases in importance with decreasing latitude.

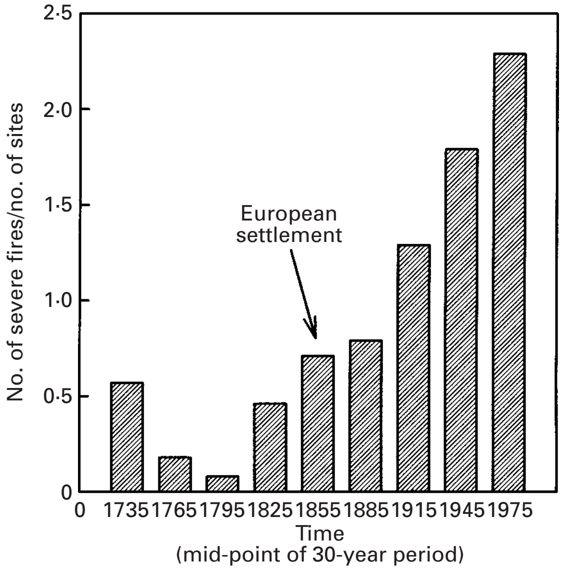

Figure 3. The change in fire intensity associated with European colonization in southwestern Western Australia. The proportion of sites with at least one fire-damaged *Eucalyptus marginata* tree ring in 30-year periods is shown. The total number (n) of sites is 14, but there are fewer than 14 sites which had *E. marginata* stems alive prior to AD 1800: the number of sites with stems in AD 1720–1750 time period is seven; for AD 1750–1780 $n = 11$; for AD 1780–1810 $n = 12$. At each site 5–10 *E. marginata* stems were sectioned. Adapted from Burrows *et al.* (1995).

Aborigines intentionally altered habitats to favour wildlife. For example, the missionary George Augustus Robinson, who travelled with Tasmanian Aborigines, reported that the Aborigines beat out fires in order to create small unburnt patches of vegetation to provide kangaroos with shelter (Jones, 1969). The explorer Ludwig Leichhardt in 1847 wrote that Aboriginal landscape burning was designed systematically to 'attract game to particular spots' (Hallam, 1985). Considering a long time-frame, in 1848 Major Mitchell conjectured that open woodlands in western New South Wales were the product of deliberate burning, a point of view he succinctly put in an oft-quoted passage that 'fire, grass, kangaroos and human inhabitants seem all dependent on each other for existence in Australia'. Furthermore, Mitchell contended that were it not for this burning, the landscape would be a 'thick jungle' rather than 'open forests' (Jones, 1969), and that this burning was a form of 'considerable labour' performed by Aborigines 'from infancy' (Hallam, 1975). The historical record also suggests that some European explorers understood that fire was important in the management of food plants. Hallam (1975, 1985) reports that in 1841 the explorer George Grey described the burning of *Typha* swamps by Aborigines in southwest Western Australian as 'a sort of cultivation'.

The magnificent synthesis by Hallam (1975) of the ethnohistorical record for the southwest of Western Australia (Fig. 1) led her to conclude that 'the land the English settled was not as God made it. It was as the Aborigines made it'. McBryde & Nicholson (1978) cautioned that Hallam's (1975) argument concerning the profound and skilful environmental management of the southwest Western Australian environments required independent corroboration before it could be uncritically accepted. Recent dendrochronolgical analyses provide such independent support (Burrows, Ward & Robinson, 1995) (Fig. 3), by showing that there was a dramatic change in the frequency of intense forest fires in southwest Western Australia following European colonization.

In aggregate, 19th century records conclusively demonstrate that 'fire was the indispensable agent by which Aboriginal man extracted many of his resources from the environment' (Nicholson, 1981). Whether Aborigines had a systematic and predictive ecological knowledge cannot be resolved from the ethnohistorical record, although some evidence supports this view.

2. *Ethnographic evidence: an anthropological blind spot*

In contrast to the relatively rich 19th century record of Aboriginal landscape burning, this topic has been largely neglected by the 20th century discipline of anthropology. For example, in 1971 the anthropologist Gould (1971) wrote that 'despite the demonstrated importance of this question, there exist as yet no holistic and empirical studies of fire as employed by any particular ethnographic hunting-and-gathering society in the world'. The cause of this intellectual blind spot, sometimes called 'the forgotten side of ethnogeography' (Stewart, 1954), is not clear. Lewis (1982) suggests that it may have come about because anthropologists assume that hunter-gathers had a passive relationship with their environment, and because Euro-American anthropologists have a culturally ingrained view that fire is a purely 'destructive environmental force'. The fundamental objective of many anthropological studies of Australian Aborigines was to learn about the 'evolution' of European culture by studying a society thought to be unusually 'primitive' (Hiatt, 1996). In these projects little thought was given to ecological relationships between humans and landscapes. Further, some authors believe that the aims and objectives of European land management are fundamentally different from those of traditional Aborigines, so ethnographic studies are unable to inform debates on how best to manage fire in landscapes settled by Europeans (Kohen, 1996). For instance, Braithwaite (1992) argues that European land managers consider landscape burning an 'emergent property' of numerous individual fires. He assumed, based on no published evidence, that Aborigines used fire in an individualistic and uncoordinated fashion with little conceptualization of the total effect of their collective burning.

Another reason for anthropological neglect is the view that 'traditional' Aboriginal landscape burning practices were corrupted following contact with Europeans, and therefore studies of contemporary burning practices cannot inform debate about the fire ecology of landscape prior to 1788 when European colonization commenced (Gill, 1977; Braithwaite, 1992). This view has been roundly criticized by Lewis (1989). He points out that there is a confusion between tools and technology (e.g. just because Aborigines use butane lighters to start fires does not necessarily mean that they have lost traditional knowledge, but may instead mean that they have employed new tools and adapted their technical knowledge to suit new circumstances). Head (1994*a*) found that Aboriginal people who have been forbidden to light fires by, in their minds, ignorant and irresponsible Europeans, tenaciously hold to the view that fire is an important humanizing force in landscapes, and remain distressed by prohibitions on starting landscape fires. Nonetheless, the loss of traditional knowledge is becoming a concern to Aborigines themselves. Given the enormous and ongoing cultural changes wrought by European colonization, it is important to assess congruence in the use of fire between young and old Aboriginal people who still use tribal lands. Sadly for much of temperate Australia where European settlement has been most pervasive, there are few opportunities to record traditional knowledge.

Whatever the cause of anthropological neglect, the consequence is that for nearly all Australian environments 'detailed empirical studies regarding the specific effects which Aboriginal landscape burning practices have on vegetational zones are lacking' (Lewis, 1982). This is despite numerous calls for more ethnoecological research (Gould, 1971; Webb, 1977; Haynes, 1978; Nicholson, 1981; Stocker & Mott, 1981; Bowman & Brown, 1986; Bowman, 1996). Lewis (1989) contends that anthropological research into the Aboriginal use of fire must also shift from merely describing Aboriginal ecological knowledge to learning about Aboriginal perceptions of the role of fire in the landscape. This has special importance given recent political developments that reinstate Aborigines' rights to influence management over vast areas of Australia, including many national parks (Hughes, 1995).

The few ethnographic studies that have been conducted are remarkably consistent with the interpretations of the ethnohistorical record previously discussed (Gould, 1971; Jones, 1975, 1980; Latz & Griffin, 1978; Kimber, 1983). For example, Gould (1971) demonstrated that Western Desert Aborigines skilfully used fire to achieve a variety of specific outcomes (e.g. cooking, warmth, illumination, ceremony, ritualistic ordeals, felling of trees, clearing camps, signalling, driving game, regenerating senescent vegetation, smoking animals from burrows and asphyxiating bats in caves). Once lit, fires were left to burn and in consequence the spatial extent ranged from localized areas to large tracts of landscape depending on local conditions. In aggregate, Gould's (1971) observations demonstrate the centrality of fire in the lives of the Aboriginal people he studied which might have been overlooked by untrained eyes because of Aboriginal people's seemingly lackadaisical attitude towards fire (Stocker & Mott, 1981). Gould (1971) hypothesized that the ecological consequence of landscape burning is to

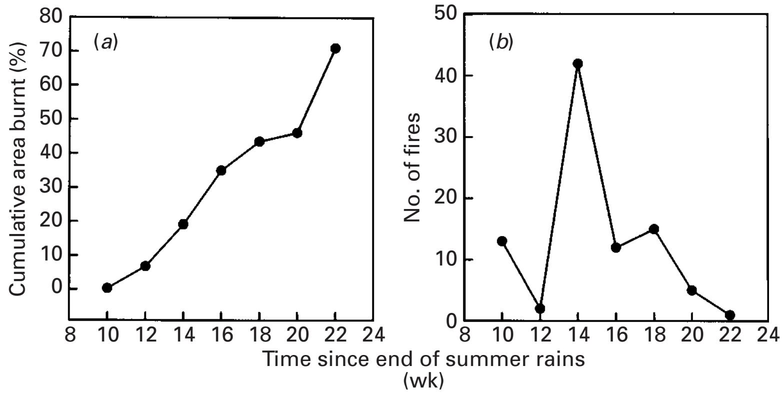

Figure 4. The cumulative area burnt (*a*) and the number of fires lit (*b*) by Aborigines to the south of Maningrida in central Arnhem Land (Fig. 1) during 1976. The large fire that occurred late in the dry season (22 wk after summer rains), at a time when fires become hard to control, was regarded by an Aboriginal informant as a 'mistake' (Haynes, 1985). With the exception of the single large late dry season fire, the area was burnt by numerous small fires creating a mosaic of burnt patches. Adapted from Haynes (1985).

increase Aborigine food supplies, and he urged ecologists to test this hypothesis experimentally. To date this challenge has not been met.

The truly extraordinary anthropological research of Thomson (1939, 1949) underlined complex and systematic temporal variation in the use of landscapes by Aborigines. Thomson (1939) concluded that 'the seasonal factor is recognized by the aborigines themselves, and stressed by the fact that they have classified the types of country, as accurately and as scientifically as any ecologist, giving to each a name, and associating it with specific resources, with its animal and vegetable foods, and its technological products'. This view was subsequently corroborated by subsequent research (Jones 1975, 1980; Haynes, 1985; Russell-Smith *et al.*, 1997). Russell-Smith *et al.* (1997) ingeniously reconstructed seasonal patterns of landscape burning in Kakadu National Park by reference to the timing of harvests of staple food plants. This work shows that prior to European colonization Aborigines must have skilfully used fire in different environments during the annual round of hunting and gathering. One important consequence of such burning was the conservation of yams (e.g. *Amorphophallus paeoniifolius*, *Dioscorea* spp. and *Ipomoea* spp.), a seasonally important source of carbohydrate. Jones (1975, 1980) spent one year with group of Aborigines in their tribal lands on the Blyth River in central coastal Arnhem Land (Fig. 1), and has eloquently described systematic and skilful burning linked with the orderly seasonal exploitation of different environments. Jones (1975,1980) found most burning occurred in the first half of the winter dry season when low-intensity fires could easily be controlled by timing ignitions with predicted climatic changes such as changes of wind or nocturnal dew falls. The burning produced a complex mosaic of burnt terrain that subsequently served as a firebreak which limited the extent of fires lit later in the year. Jones (1975, 1980) reported that in deference to vengeful supernatural beings, fire-sensitive rain forest pockets were protected from uncontrolled fires by firebreaks on their perimeters. Haynes (1985) has similarly described how Aborigines near Maningrida in central Arnhem Land (Fig. 1) used low-intensity fires to create a mosaic of burnt areas throughout the dry season (Fig. 4). One consequence, explicitly understood by Aborigines, was conservation of the fire-sensitive native conifer *Callitris intratropica* on sites without any topographic protection from fire. The importance of fire regimes in controlling the demography of *Callitris intratropica* has been demonstrated by Bowman & Panton (1993*a*) and Price & Bowman (1994).

An incontrovertible fact that emerges from the sparse ethnographic literature is that fire was a powerful tool that Aborigines used 'systematically and purposefully over the landscape' (Russell-Smith *et al.*, 1997). Tragically, the details of such fire management have not been adequately documented, although remote sensing and geographic information system technologies provide a powerful approach to studying the current uses of fire by Aborigines (O'Neill, Head & Marthick, 1993). The ethnographic record also underscores an important difference between European and Aboriginal fire management. Unlike Europeans, Aborigines did not have the technological means to extinguish landscape fires. Instead, their control appeared to hinge on predicting the behaviour and spatial extent of fire.

III. ECOLOGICAL PERSPECTIVES

1. *Landscape ecology : random or non-random fires?*

It is generally accepted that fire plays a central role in nearly all Australian terrestrial ecosystems by stimulating regeneration and determining demographic patterns of trees (Gilbert, 1959; Jackson,

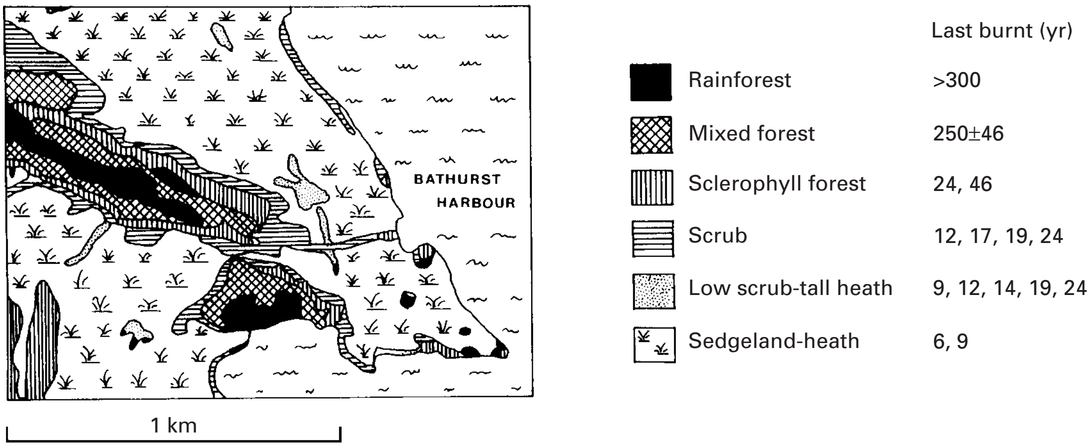

Figure 5. Vegetation map of a small area at Bathurst Harbour in southwest Tasmania. The estimated times since the last fire in various stands of each vegetation type are shown. Adapted from Brown & Podger (1982).

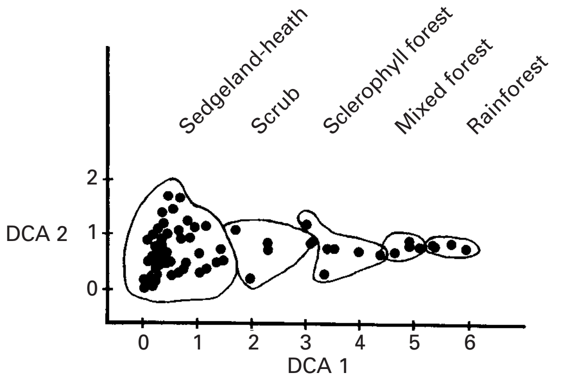

Figure 6. Ordination of floristic quadrat data collected from different vegetation types at Bathurst Harbour. The first axis of the detrended correspondence analysis ordination (DCA1) is strongly correlated with the time since the last fire. Adapted from Brown, Ratkowsky & Minchin (1984).

1968; Ashton, 1981; Bowman, 1986), influencing vegetation structure (Gilbert, 1959; Braithwaite & Estbergs, 1985; Bowman & Panton, 1995) and determining the distribution of fire sensitive vegetation such as rain forest and *Callitris*-dominated communities (Gilbert, 1959; Tindale, 1959; Jackson, 1968; Webb, 1968; Brown & Podger, 1982; Smith & Guyer, 1983; Ash, 1988; Unwin, 1989; Bowman, 1992*a*; Russell-Smith & Bowman, 1992; Bowman & Latz, 1993; Bowman & Panton, 1993*a*; Harrington & Sanderson, 1994). Brown & Podger (1982) provide a superb example of a successional sequence from sedgeland to rain forest at Bathurst Harbour in southwest Tasmania (Fig. 1) that corresponds to the time elapsed since the last fire (Figs 5, 6). Currently, lightning accounts for very few fires in natural vegetation in Tasmania (Jackson & Bowman, 1982*a*; Podger, Bird & Brown, 1988), so the pre-European distribution of sedgeland may have been largely a product of frequent Aboriginal burning (e.g. Jackson, 1968; Macphail, 1980; Bowman & Jackson, 1981; Brown & Podger, 1982; Podger *et al.*, 1988; Thomas, 1993, 1995), although this conclusion is disputed by some scholars (Mount, 1979; Cosgrove, Allen & Marshall 1994).

Some authors have specifically invoked past Aboriginal landscape burning to explain particular demographies of trees (e.g. Bowman & Kirkpatrick, 1984, Bowman & Panton, 1993*a*), and vegetation distribution patterns, particularly rain forest boundaries (e.g. Herbert, 1938; Jackson, 1968; Ellis, 1985; Ash, 1988; Russell-Smith *et al.*, 1993; Fensham & Fairfax, 1996). For example, the rapid expansion of rain forests into treeless grasslands, and the change from low to high densities of trees in *Eucalyptus* forests, has been attributed to a decrease in fire frequency following the cessation of Aboriginal landscape burning (Jackson, 1965; Bowman & Kirkpatrick, 1984; Ellis, 1985; Ash, 1988; Bowman, Panton & McDonough, 1990; Duncan, 1990; Fensham & Fairfax, 1996).

In contrast to the putative effects of Aboriginal burning, European fire regimes have been shown to have resulted in the range contraction of the long-lived endemic Tasmanian conifers such as *Lagarostrobos franklinii*, *Athrotaxis selaginoides* and *Athrotaxis cupressoides* (Cullen, 1987; Cullen & Kirkpatrick, 1988; Gibson & Brown, 1991); the monsoon rain forest tree *Allosyncarpia ternata* endemic to the Arnhem Land Plateau (Russell-Smith *et al.*, 1993; Bowman, 1994); and the native conifer *Callitris glaucophylla* in the Macdonnell Ranges of central Australia (Bowman & Latz, 1993) (Fig. 1). Conversely, Harrington & Sanderson (1994) suggest that the expansion of rain forest on the Atherton Tablelands in north Queensland is linked with a decline in fire intensity associated with a change from Aboriginal fire management to pastoralism. In the monsoon tropics, the contraction or expansion of *Callitris intratropica* (Bowman & Panton, 1993*a*) and the boab, *Adansonia gibbosa* (Bowman, 1997), is thought to correspond to localized changes in fire frequency and intensity. Podger *et al.* (1988) also note that in Tasmania some rain forests expanded while others contracted following European colonization, and they suggest that the resolution of these differences may lie in local ecological factors such as terrain, soils and the history of fire use. Woinarski (1997) reviewed the effects of fire on Australian birds. He concluded that although there is a variable response of birds to various fire regimes, the extinction or threat of extinction of about 10% of the Australian terrestrial avifauna is probably linked with a change in fire regime following European colonization. Post-European colonization fire regimes are thought to have disfavoured some bird species by the destruction of suitable habitats.

Impacts of European colonization and frequency of intense fires is well illustrated by dendrochronological research. Pulsford, Banks & Hodges (1993) provide an excellent case study of the combined impact of burning, cattle grazing, and rabbit browsing on *Callitris glaucophylla* in the Snowy River Valley in New South Wales (Fig. 1). These authors demonstrated that the transition from Aboriginal to European land use resulted in a sudden occurrence of fire-damaged tree rings thought to reflect a shift from low-intensity to high-intensity fires. A similar change in fire regime has been inferred from dendrochronological studies in *Eucalyptus marginata* forests in southwest Western Australia (Burrows *et al.*, 1995), and *Eucalyptus pauciflora* in the Brindabella Ranges near Canberra (Fig. 1) (Banks, 1988). Burrows *et al.* (1995) have shown that prior to European settlement the mean time interval between fires that produced fire-damaged tree rings was about 80 years. Following European colonization, especially after the 1847 Bushfire Ordinance, which sanctioned the flogging of minors and Aborigines who lit fires, the frequency of injurious fires increased to a mean of less than 20 years (Fig. 3) presumably because of increased fuel loads. Low-intensity fires are not registered by dendrochronological analyses, but given the fire-prone environments in which *Callitris glaucophylla*, *Eucalyptus marginata* and *Eucalyptus pauciflora* occur, the absence of fire scars cannot reasonably be interpreted as an absence of fires (Burrows *et al.*, 1995). The dendrochronological interpretation that European colonization increased the frequency of fires sufficiently intense to damage trees in *Eucalyptus* forest environments is consistent with interpretations of the historical record (King, 1963).

It must be conceded that all of the above studies are based on circumstantial evidence. There are remarkably few studies that determine the direct ecological impact of Aboriginal landscape burning. However, Bowman (1993*a*) documented the boundary dynamics of a rain forest in an area regularly burnt by Aborigines on Melville Island (Fig. 1), and concluded that over a 22-year period Aboriginal fires had caused limited damage to isolated patches of rain forest. A number of field and pot trials have disproved the hypothesis that frequent fires, assumed by some to have been caused by Aborigines (e.g. Stocker & Mott, 1981), prohibit the establishment of rain forest in tropical savanna. These experimental studies demonstrated that although unburnt savanna develops dense understoreys, this structural change is not accompanied by rapid establishment of rain forest seedlings (Fensham, 1990; Bowman & Fensham, 1991; Bowman & Panton, 1995) possibly because of unfavourable soil microbiota in monsoonal *Eucalyptus* savannas (Bowman & Panton, 1993*b*). However, development of dense understoreys in unburnt savannas was found significantly to affect the fauna (e.g. by increasing the diversity of species and abundance of leaf-litter ants (Andersen, 1991) and frugivorous birds (Woinarski, 1990)). Unfortunately, the rampant establishment of weeds and exotic vertebrates, and the fragmentation of habitats following clearing, have probably irreversibly changed the fire ecology of some Australian landscapes (e.g. Kitchener *et al.*, 1980) potentially precluding experimental elucidation of the nature and ecological consequences of Aboriginal fire regimes.

In order to comprehend the long-term dynamics of different vegetation types, some authors have used a modelling approach. In most of these models, the occurrence of ignition sources is assumed to be random in time or space such that fire in each vegetation type is assumed to have a particular probability distribution (Jackson, 1968; Henderson & Wilkins, 1975; Green, 1989; Bradstock *et al.*, 1996; Noble & Gitay, 1996). However, the assumption of random ignition sources is unrealistic because Aborigines intentionally started fires at particular times and places in the landscape (Ellis 1965; Jackson, 1968; Brown & Podger, 1982; Jackson & Bowman, 1982*b*). Therefore, without modification these models cannot provide insight into the long-term impact of Aboriginal landscape burning. By contrast, Price & Bowman (1994) constructed a staged-based matrix model explicitly to determine the combination of fire periodicities and fire intensities required to produce the demographic structures of the native north Australian conifer *Callitris intratropica* observed by Bowman & Panton (1993*a*) in the Northern Territory. The results of the model suggest that a regime of intense infrequent fires, such as would be caused by lightning storms at the end of the dry season (Bowman, 1988), would result in the local extinction of the conifer (Fig. 7). Under this ‘natural’ fire regime, *C. intratropica* would ultimately be restricted to sites with topographic fire protection, such as boulder fields and canyons which presently support fire-sensitive monsoon rain forests (Bowman, 1992*a*). Annual fires, which characterize European fire management, were found severely to reduce the

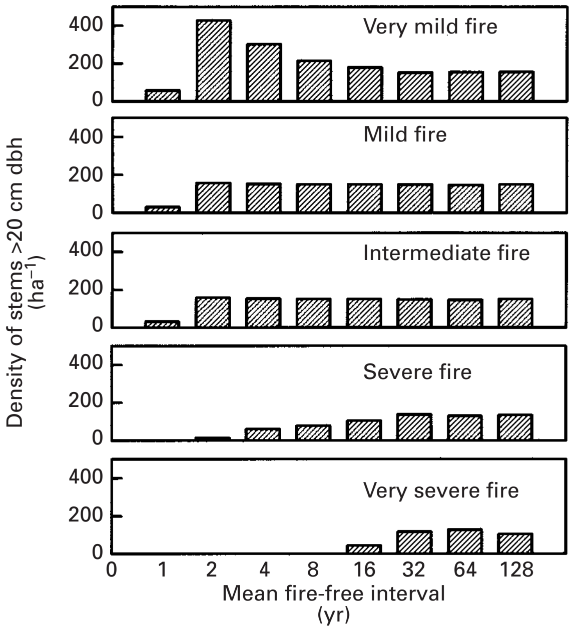

Figure 7. The density per hectare of mature *Callitris intratropica* stems (> 20 cm dbh) under various combinations of fire intensity and fire frequency as determined by a mathematical model run for 300 yr. The results are averaged values for the last 100 yr of the simulation. Adapted from Price & Bowman (1994).

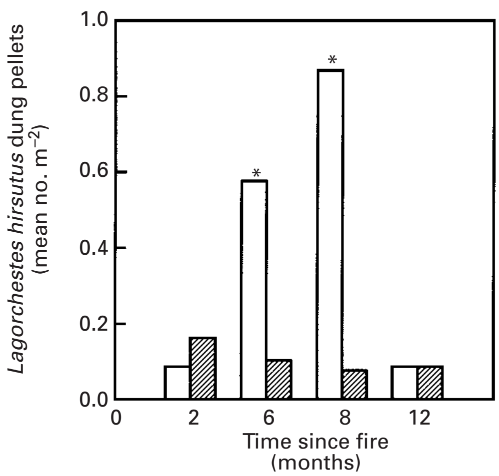

Figure 8. Change in the density of rufous hare-wallaby (*Lagorchestes hirsutus*) dung per m^2 on an unburnt site (shaded bars) and an adjacent burnt site (unshaded bars) over a 12-month period. *F*-statistics were used to test for differences between burnt and unburnt quadrats (*, $P < 0{\cdot}01$). Adapted from Lundie-Jenkins (1993).

density of *C. intratropica* trees, and would ultimately lead to their localized extinction on sites without topographic fire protection. This is because seedlings less than 1 yr old cannot tolerate even low-intensity fires (Fig. 7). Stands with the highest density of mature stems > 20 cm dbh were found to arise only under a regime of very mild fires with a periodicity of between 2 and 8 years (Fig. 7). Price & Bowman (1994) argue that the model implies that the vast tracts of *C. intratropica* that occur on sandsheets (i.e. sites with no topographic fire protection) in the coastal regions of the Northern Territory (Wilson *et al.*, 1990) are the product of skilful use of fire by Aborigines.

In summary, there is a large body of circumstantial evidence which suggests that altered fire regimes following the cessation of Aboriginal land management have resulted in substantial changes in the range and demographic structure of many vegetation types, such as rain forest, with corresponding changes in animal populations. However, there has been limited experimental investigation of the impacts of Aboriginal landscape burning, possibly because sufficiently sophisticated fire experiments are difficult to perform, and simple experiments yield results that are controversial (e.g. Lonsdale & Braithwaite, 1991; Bowman, 1992*b*). Modelling has corroborated the potential importance of Aboriginal fire regimes in the maintenance of one species of tree in the monsoon tropics, and there is potential further to employ models.

2. *Mosaic burning: manufacturing small mammal habitats?*

A puzzling problem in Australian ecology is the cause of the extinction of many mammals mainly restricted to arid Australia and ranging in weight from 0·035 to 5·5 kg, following European colonization (Burbidge & McKenzie, 1989). One explanation for this extinction is habitat changes following European colonization. It may be that a long history of Aboriginal landscape burning created a habitat mosaic that was critical for the maintenance of a diverse small mammal assemblage (Bolton & Latz, 1978; Kitchener *et al.*, 1980; Burbidge *et al.*, 1988; Burbidge & McKenzie, 1989). However, Morton (1990*a*) has developed a convincing alternative explanation of the small mammal extinctions and the contrasting survival of all reptiles and nearly all bird species in arid Australia. He argues that small mammal extinctions were a consequence of competition with stock and other introduced herbivores (rabbits, sheep, goats, cattle, donkeys, horses and camels) and predation by introduced carnivores (cats, foxes and dogs), particularly during droughts when the native small mammals were restricted to localized, ecologically productive habitats.

There have been few tests of the hypothesis that mosaic burning maintains wildlife habitats. All have focused on arid ecosystems. Short & Turner (1994) found no evidence that three mammals in the 'critical weight range' of Burbidge & McKenzie (1989) depended upon habitat heterogeneity caused by either burning or oil exploration on Barrow Island, a continental island off the northwestern West Australian coast (Figure 1). They concluded that the loss of small mammals throughout central Australia and their contrasting survival on continental islands is best explained by the impact of introduced carnivores and possibly herbivores rather than being linked to changes in fire regime. Indeed, practical experience has shown that control of introduced predators (cats, foxes and dogs) is critical for successful reintroduction programmes (Short *et al.*, 1992; Smith & Quin, 1996). Frequent burning which produces open habitats may increase predation of animals that are not able to burrow or which are not cryptic (Smith & Quin, 1996). However, in the Tanami Desert (Figure 1), the rufous hare-wallaby (*Lagorchestes hirsutus*) is attracted to burnt areas of *Triodia* grasslands that are less than 12 months old, possibly because the regrowing vegetation is more nutritious and palatable (Lundie-Jenkins, 1993) (Figure 8). This finding is consistent with the suggestion of Bolton & Latz (1978) that the survival of this macropod species would have been favoured by Aboriginal landscape burning which created a mosaic of *Triodia* grasslands with different fire histories. A management recommendation of Lundie-Jenkins (1993) was the creation of such a habitat mosaic in the Tanami Desert. However, the optimal spatial scale of burnt patches and the appropriate frequency of burning to achieve favourable habitat for mammals like *Lagorchestes hirsutus* are not known and requires investigation. There is some evidence that small mammals in heathlands in temperate Australia and macropods in rain forests on the eastern seaboard of Australia may also have benefited from Aboriginal burning (Stoddart & Braithwaite, 1979; Johnson, 1980; Vernes, Marsh & Winter, 1995). Much more research into the relationship between mammals and the age of vegetation since the last fire remains to be carried out throughout Australia (Fox & McKay, 1981).

Thus, limited available evidence supports the potential importance of Aboriginal landscape burning in creating habitat mosaics for small mammals in some environments. The widespread extinction of small mammals in arid environments appears primarily linked to the introduction of carnivores and large ungulate herbivores by Europeans.

IV. PALAEOECOLOGICAL PERSPECTIVES

1. *Initial impact of Aboriginal colonization: a question ahead of its time*

The question of the original impact of humans on the Australian continent is fascinating, but the debate has not advanced substantially in the last 20 years (Head, 1994*b*). The arguments are fundamentally speculative because there is no agreed timetable for the arrival of humans in Australia. As late as 1961, it was assumed that Aborigines had colonized Australia in the Holocene (Jones, 1979). Rather than precisely dating the arrival of humans in Australia, subsequent archaeological research using both radiocarbon and luminescence dating techniques has steadily extended the time of Aboriginal occupancy (Chippendale, 1996). The currently most conservative accepted time for the commencement of Aboriginal colonization is 40000 years BP, which is the upper threshold of radiocarbon dating (Allen, 1994; Allen & Holdaway, 1995). However, because of limitations of radiocarbon dating, Chappell, Head & Magee (1996) argue for reliance upon luminescence dating. Dates derived from thermoluminescene and optical luminescence extend the occupancy of humans to 50–60000 BP in Kakadu National Park in northern Australia (Roberts, Jones & Smith, 1990; Roberts *et al.*, 1994), although this is not universally accepted (Hiscock, 1990; Bowdler, 1991; Allen, 1994; Allen & Holdaway, 1995). Recently, a controversial paper using themoluminescene dating has suggested that humans were present in northwestern Australia as far back as 120000 BP or more (Fullagar, Price & Head, 1996).

The timing of settlement patterns across the continent also are poorly known, although southwestern Western Australia was definitely occupied by about 40000 BP (Pearce & Barbatti, 1981); Tasmania was definitely occupied by about 35000 BP (Cosgrove, 1989); and Aborigines were in central Australia by at least 27000 BP and probably remained there enduring the height of full glacial aridity around 18000 BP (Smith, 1987,1989). It is not known how many waves of human colonization occurred, or what was the genetic composition of the colonists. Some scholars have suggested that both anatomically modern and anatomically archaic humans independently colonized Australia in the Pleistocene and subsequently coexisted and ultimately hybridized (Thorne & Macumber, 1972; Thorne, 1977; Jones, 1979; Thorne & Wolpoff, 1981,1992).

It is not far fetched to assume that the first Aboriginal colonists of Australia were skilled in using fire (Jones, 1979; Head, 1989; Kohen 1996). Indeed, it has been suggested that the spread of cattle (*Bos*) species throughout Southeast Asia was facilitated by anthropogenic burning which created suitable habitats (Wharton, 1969). Certainly, the strong similarities of floras within the Old World tropics would have meant that the first colonists were familiar with most of the plant genera, and many of the plant species, in northern Australia (Golson, 1971; Bowman, Wilson & Dunlop, 1988; Liddle *et al.*, 1994).

2. *Archaeology: residues of habitation and the invisibility of habits*

Aboriginal burning of landscapes is invisible in the archaeological record (Thomson, 1939). Indeed, as the case of the Tasmanian Aborigines demonstrates, there is no relationship between the complexity of tool kits in the archaeological record and level of sophistication in the use of fire to modify landscapes. At the time of European contact, the Tasmanian

Aborigines had the simplest tool kit of any cultural group in the world, exemplified by the fact that they appear to have lost the technological means to make fire *de novo* (Jones, 1977). Paradoxically, there is ethnohistorical and ecological evidence that these people used fire so skilfully that they were able to maintain treeless vegetation in otherwise forested environments (Jones 1969; Jackson, 1968; Macphail, 1980; Macphail & Colhoun, 1985; Thomas, 1993, 1995) (Figs 5, 6). Yet, in the very landscape burnt by Aborigines, there were large tracts of fire-sensitive vegetation including some conifers (i.e. *Athrotaxis* spp.) that live for over 2000 yr (Bowman & Brown, 1986; Cullen, 1987; Cullen & Kirkpatrick, 1988). European colonization and associated burning has caused the massive decline of such fire-sensitive vegetation in Tasmania. For example, landscape fires in the last 100 years have resulted in the loss of about 30% of the total coverage of the Tasmanian endemic conifer *Athrotaxis selaginoides* (Brown, 1988).

There are very few detailed studies that specifically link archaeological and palaeoecological data to determine the impact of Aboriginal landscape burning. Smith, Vellen & Pask (1995) reported changes in the species composition of charcoal fragments collected during an archaeological excavation of a rock shelter in central Australia. They show that the species composition of charcoals assumed to have originated from campfires changed through time from the commencement of occupation about 27000 BP until the late Holocene. Some of these changes are assumed to reflect the response of local vegetation to climate change, although they suggest that there was a decline of the prized fuel-wood *Callitris glaucophyll*a in the late Holocene reflecting the impact of frequent burning. However, I suggest that their data do not show any clear temporal trend in the number of *C. glaucophylla* charcoal fragments. Moreover, their interpretation is inconsistent with available ecological evidence. Bowman & Latz (1993) argue that a recent decline of *C. glaucophylla* in central Australia is because of a decreased frequency of fires associated with the cessation of Aboriginal landscape burning after European colonization.

In one of the most comprehensive studies that linked palynology with archaeology, Head (1988) concluded that Aboriginal landscape burning during the last 7000 years had no detectable impact on the coastal ecosystems at Discovery Bay in southwestern Victoria (Fig. 1). Working in northeast Tasmania, Ellis and Thomas (1988) used archaeological, palynological and ecological data to form the conclusion that Aboriginal burning was responsible for the localized maintenance of grasslands within large tracts of rain forest. Although palynologists and ecologists also attribute treeless tracts in southwest Tasmania to prehistoric Aboriginal burning (Jackson, 1968; Macphail, 1980; Macphail & Colhoun, 1985), archaeologists are divided over this. Archaeological evidence from caves points to the abandonment of southwestern Tasmania at the end of the Pleistocene (Cosgrove, Allen & Marshall, 1990; Cosgrove *et al.*, 1994), although Thomas (1993) argues that the absence of archaeological material in caves merely reflects a change in local settlement patterns.

3. *Palynology and Aboriginal landscape burning: ashes and dust*

Given the effective invisibility of Aboriginal burning in the archaeological record, most inferences about prehistoric burning hinge on pollen and microscopic charcoal from swamp and lake sediments. This is an enormously complex and controversial topic because of different temporal frameworks and spatial scales used by palynologists (Clark, 1983; Head, 1986, 1989; Thomas, 1993) and difficulties of interpreting microscopic charcoal data (Clark, 1983; Head, 1989; Ladd, 1988). Microscopic charcoal particles demonstrate the occurrence of a fire within an unknown catchment area in the vicinity of a given pollen core but provide no information concerning the spatial extent or season of a fire. Most palynological studies are of low resolution, where a single sample may contain sediments laid down over 10–100 years. In such samples, charcoal concentrations are confounded by post-fire erosion events, fire frequency and fuel quantity. Nevertheless, by using extremely fine-scale palynology, Green *et al.* (1988) have demonstrated a significant statistical correlation between charcoal particles and *Eucalyptus* tree-ring damage caused by single fire events. In Australia such detailed studies are exceptional.

Much palynological research that emphasizes the importance of Aboriginal landscape burning was designed to study regional climate change. Thomas (1993) argues that such regional studies are unsuitable for advancing the question of the impacts of Aboriginal landscape burning. He advocates coupling archaeological research with fine-scale pollen analyses that focus on local taxa. Unfortunately, there are few such studies (Ellis & Thomas, 1988; Head, 1988).

The main argument for a major impact of Aboriginal burning concerns three long pollen cores, one from southeastern Australia and two from northeast Queensland. In all three, a dramatic increase in charcoal particles was correlated with the first occurrence of fire-adapted vegetation assumed to be dominated by *Eucalyptus* (Fig. 9). However, that Aboriginal landscape burning had a massive impact on vegetation is not universally accepted. A number of authors have cast doubt on the interpretation of these long-term pollen cores, and have marshalled contravening palynological evidence

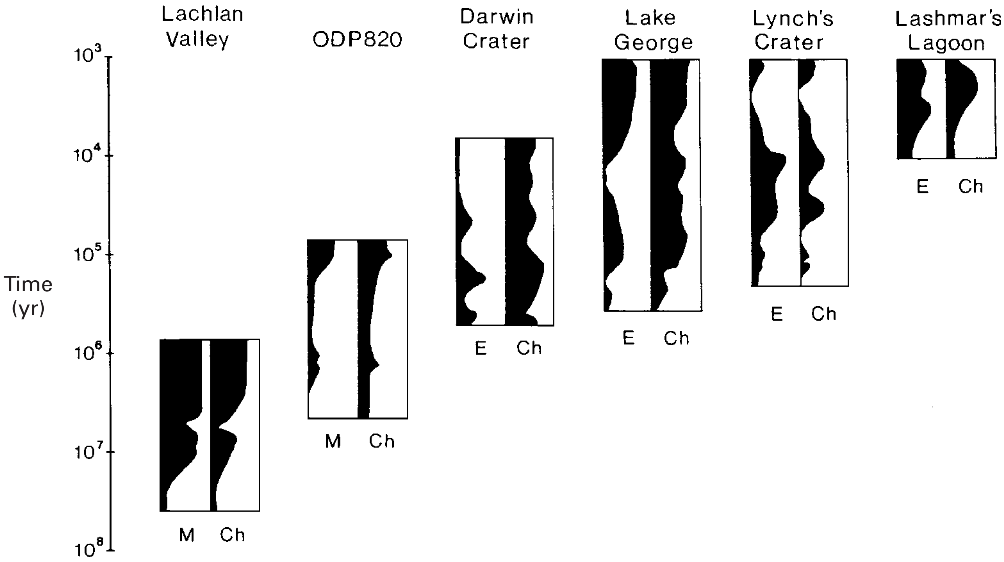

Figure 9. Variation in the relative abundance of Myrtaceae pollen (M) or *Eucalyptus* pollen (E) and microscopic charcoal particles (Ch) from cores at various sites in northeastern and southeastern Australia. The time scale is logarithmic and the abundance of pollen and charcoal indicative. Adapted from Martin (1987) for Lachlan Valley; Kershaw *et al.* (1993) for OPD 820; Colhoun & van de Geer (1988) for Darwin Crater; Singh *et al.* (1981) for Lake George; Kershaw (1983, 1986) for Lynch's Crater; and Singh *et al.* (1981) for Lashmar's Lagoon.

(Horton, 1982; Clark, 1983; Head, 1989; White, 1994). I shall treat this topic in detail because it has assumed primacy in the debate concerning the impact of Aboriginal landscape burning. First, I review evidence from the three long pollen cores, and then I consider the general significance of palynological and charcoal evidence.

(*a*) *Lake George:* Casuarina *and uncertainty*. Singh & Geissler (1985) argued that a pollen record spanning the last 350000 yr from Lake George in southeastern Australian (Fig. 1) provides clear evidence of major modification of the surrounding vegetation by Aboriginal burning in the last interglacial. Unlike previous interglacials, where *Casuarina* was the dominant woody plant, the vegetation that developed sometime around 128000 BP was fire-adapted and dominated by *Eucalyptus*. The crux of their argument is that such fire-adapted vegetation could not be a consequence of climate change and therefore is reasonably interpreted as an effect of Aboriginal burning. However, the pre-radiocarbon chronology for Lake George was based on climates inferred from oxygen-isotope records preserved in deep-sea cores, and has been questioned (Horton, 1982; Wright, 1986*a*; Head, 1989). Wright (1986*a*) specifically disputes the 128000 BP date for the transition from *Casuarina* to *Eucalyptus*, which predates all but one archaeological site (Fullagar *et al.*, 1996) by more than 60000 yr. Wright used a simple linear regression of depth against radiocarbon dates to extrapolate the age of *Eucalyptus* dominance, and concluded that the actual date is 54000 yr. Wright's interpretation is consistent with archaeological evidence for the first arrival of humans in Australia around 50–60000 BP (Roberts *et al.*, 1990, 1994), but may be flawed because it assumes a constant rate of sedimentation (Kershaw *et al.*, 1991; Kershaw, 1994*a*).

A number of authors have disputed that *Casuarina* (including the extremely closely related genus *Allocasuarina* that is not differentiated here) is a good indicator of fire-sensitive vegetation (Horton, 1982; Clark, 1983; Ladd, 1988; Head, 1989; Thomas & Kirkpatrick, 1996). The relationship between high levels of charcoal and *Casuarina* is inconsistent within the Lake George core and in other cores. For example, high levels of charcoal do not coincide with reduced abundance of *Casuarina* in the period 64000–22000 BP (Horton, 1982; Clark, 1983; Head, 1989). Kershaw *et al.* (1991) present pollen data from four sites in the western plains region of western Victoria and southeastern South Australia (Fig. 1). Their data show inconsistent relationships between charcoal particles, *Casuarina* and *Eucalyptus* pollen in the late Pleistocene and Holocene. Horton (1982) notes that the mid-Holocene decline of *Casuarina* in a core from Lashmar's Lagoon on Kangaroo Island (Fig. 1) was not related to any change in low levels of microscopic charcoal particles. This decline may have occurred about 2000 yr before the island was abandoned by Aborigines (Singh, Kershaw & Clark, 1981). Moreover, *Casuarina* pollen in Lynch's Crater and ODP 820 cores (Fig. 1) is associated with high levels of microscopic charcoal particles. The analysts of these cores (Kershaw, 1986; Kershaw, McKenzie & McMinn, 1993) consider *Casuarina* a component of a fire-adapted vegetation type. After considering numerous pollen records from the Holocene, Clark (1983) formed the view that 'there is no direct correlation between the decline of *Casuarina* in the Holocene and Aboriginal landscape burning'. Indeed Thomas & Kirkpatrick (1996) demonstrate that *Casuarina* replaced *Eucalyptus* following intensive use of a site in northeastern Tasmania in the mid-Holocene. They attribute the replacement of *Eucalyptus* to soil podzolization, salt-spray, and increased burning by Aborigines.

These apparently contradictory results may be explained by different responses of *Casuarina* species to fire (Ladd, 1988). For example, the dominant *Casuarina* species on the Atherton Tableland (*C. torulosa*), has been shown to be tolerant of recurrent fires (Kellman, 1986) but *Casuarina stricta* in southeastern Australia is favoured by fire protection (Withers & Ashton, 1977). A review of the ecology of *Casuarina* led Ladd (1988) to conclude that the genus should primarily be considered drought-adapted with well-developed ability to recover from fire. He suggests that the decline of *Casuarina* in the Lake George core may be linked with a wet climate that favours *Eucalyptus*, large fuel loads and frequent fires. It is possible that the decline of *Casuarina* in the Lake George cores is the continuation of a long-term trend that commenced in the Tertiary. For example, a deep-sea core off the coast of northwestern Australia, ODP 765 (Fig. 1), shows that *Casuarina* dominance has been in decline since the late Miocene (Martin & McMinn, 1994).

(*b*) *Lynch's Crater: a late Pleistocene rain forest set ablaze?* Kershaw (1986) has interpreted the vegetation history of a core at Lynch's Crater as spanning two glacial–interglacial cycles (Figs 1, 9). In general Kershaw shows that humid tropical rain forest, which currently dominates the vicinity, also occurred there during the two previous interglacials. During dry glacial periods the vegetation was dominated by *Araucaria*, a genus of drought-adapted rain forest conifers restricted to the Southern Hemisphere. Commencing at approx. 38000 BP, a transition from *Araucaria*-dominated rain forest to *Eucalyptus* occurred. This transition was accompanied by a dramatic increase in microscopic charcoal and apparent extinction of the rain forest conifer *Dacrydium*. Kershaw (1986) rejects the hypothesis that the decline of drought-adapted rain forest and the dominance of *Eucalyptus* forest was a consequence of climate change because the transition is unlike all others in the core. He believed that this reflected the impact of burning by colonizing Aborigines. Although Clark (1983) agreed that the extinction of *Dacrydium* and the reduced abundance of *Araucaria* and *Podocarpus* might be a consequence of Aboriginal landscape burning, she did not unequivocally accept that this caused all the changes in the Lynch's Crater core. For example, she suggested that the increase in microscopic charcoal particles might be the result of a number of factors such as the drying of the lake and subsequent fires on its surface, or increased fires in the region in response to a drier climate and more open vegetation. However, Head (1989) finds these alternative hypotheses unconvincing and therefore supports Kershaw's interpretation.

Kershaw's (1986) interpretation appears consistent with sparse available biogeographic data. Although little is known about the response of *Araucaria* to burning, abrupt *A. cunninghamii* and *A. bidwillii* boundaries with grassland and *Eucalyptus* forest suggest that the distribution of this group is controlled by fire (Cromer & Pryor, 1943; Webb, 1964; Fensham & Fairfax, 1996). Radiocarbon dating of macroscopic charcoal from rain forest soil in northeast Queensland has shown that *Eucalyptus* forests, and associated fires, were widespread during the late Pleistocene (Hopkins *et al*., 1990, 1993). Hopkins *et al*. (1993) suggest that dry and possibly frost-prone climates that favour fires may be linked to the occurrence of *Eucalyptus* forest. The cause of such fires is not known, but both Aborigines and lightning would have been important ignition sources. These authors suggest that the expansion and contraction of *Eucalyptus* forest was not synchronous everywhere. Instead, it reflected local site factors, such as rainfall, topography, soils, and proximity to adjoining *Eucalyptus* forests.

Spatial variation in rain forest expansion is demonstrated by studies conducted by Hopkins *et al*. (1996) on the coastal lowland in northeast Queensland, who argued that *Eucalyptus* forests occurred as late as 1400 BP in an area now dominated by rain forest. They explain the contrasting late Holocene establishment of rain forest in the lowlands versus the early Holocene expansion of rain forest in the highlands as a consequence of increased Aboriginal populations and associated burning associated with the drowning of the coastal plain during the early Holocene. Alternatively, they suggest that the combined effect of Aboriginal burning and relatively drier late Holocene climates may have caused the re-expansion of *Eucalyptus* into fire-prone sites. Nonetheless, Aboriginal burning did not cause the total destruction of rain forest, as evidenced by concentrations of numerous rare, monotypic, and endemic plant species. At most, Aboriginal burning probably produced a vegetation mosaic of rain forest on fire-protected sites and *Eucalyptus* on fire-prone sites (Hopkins *et al*., 1996).

(*c*) *ODP 820: a deep-sea sedimentary record of interglacial colonization?* Kershaw *et al*. (1993) examined a continuous pollen record from a deep-sea core (ODP Site 820) thought to represent 1·5 million years of sedimentation (Fig. 9). In general, the core shows that vegetation was characterized by a drought-tolerant rain forest dominated by *Arau-*

caria with some evidence of the vegetation changing in response to global climate changes and associated fluctuations in sea level. Near the top of the core, thought to represent the beginning of the last glacial cycle, the *Araucaria* rain forest is replaced by taxa thought indicative of *Eucalyptus* forests, and this transition is accompanied by abundant microscopic charcoal particles. Although Kershaw *et al*. (1993) note the possibility that these changes could reflect a long-term climate trend of 'increasingly drier and more variable climatic conditions' that has been at work since the mid-Tertiary, they favour the hypothesis that the transition is in response to Aboriginal burning. They are particularly struck by the coincidence of the vegetation change in ODP 820 and the vegetation changes described for Lake George (Singh & Geissler, 1985). Like that for Lake George, the chronology of this deep-sea core is based on oxygen isotope data.

Some features of ODP 820 are inconsistent with Kershaw *et al*.'s (1993) interpretation. First, there is a peak of microscopic charcoal particles near the base of the core, with an assumed age of 1·5 million years. Unlike the charcoal peak near the top of the core, the basal peak does not correlate with a decline of *Araucaria* pollen. Second, unlike the Lynch's Crater core where pollen of the rain forest conifers *Podocarpus* and *Araucaria* both decline with increased charcoal particles, in ODP 820 *Araucaria* but not *Podocarpus* pollen declines in the last interglacial when fire frequency is thought to have increased. Anderson (1994), Hope (1994) and White (1994) argue that the pollen and charcoal data from ODP 820 cannot be used to support an initial impact of Aboriginal burning because of sampling and taphonomic problems. They indicate that the data can be interpreted in alternative ways that do not require anthropogenesis. For example, White (1994) notes that the marine sediments may have been deposited intermittently making variation in pollen or charcoal concentrations artifactual. In response to White's criticism, Kershaw (1994*a*) agrees that Lynch's crater and ODP 820 were different depositional environments, but rejects the notion that the patterns of pollen and charcoal abundance in ODP 820 are sedimentary artefacts.

The lack of synchronicity between the ODP 820, Lynch's Crater and Lake George cores, as well as uncertainty concerning the timing of the arrival of humans, are serious impediments in the use of these cores as clear evidence of an initial destructive effect of burning carried out by colonizing Aborigines. Complicated explanations of these anomalies have been put forward, such as the idea that Aborigines were unable to colonize dense areas of rain forest, thus the impact of burning on Atherton occurred long after the initial impacts at Lake George and on the northeastern Australian continental shelf (Singh *et al*., 1981; Kershaw, 1981, 1994*a*, *b*). It is possible that subsequent research that sorts out the currently contradictory chronologies will conclusively demonstrate that the timing of the arrival of humans and the increase in burning throughout Australia are synchronous. A synchronous and acute, rather than an asynchronous and gradual, impact of Aboriginal landscape burning would be consistent with Head's (1989) proposition that Aborigines minimized their impact with fire once they learnt how the Australian environment worked. By 5000 BP, and possibly much earlier, some groups of Australian Aborigines had successfully learnt to inhabit the rain forest environment (Cosgrove, 1996). It is possible that the knowledge to survive in rain forests was brought to Australia by the first colonists from Southeast Asia (Bowdler 1983). If this were the case, there would not have been a strong motive immediately to destroy rain forests with fire.

(*d*) *Alternative perspectives and alternative evidence*. The value of palynology in providing insights into Aboriginal landscape burning has been critically discussed by a number of researchers. Many of these critiques have focused on the inconsistent and ambiguous relationship between pollen and charcoal in the Pleistocene, Holocene and transition from Aboriginal to European fire management. The changes in Pleistocene pollen cores attributed to Aboriginal landscape burning may be part of a long-term change that commenced in the Tertiary (Clark, 1983; Head, 1989; Kershaw *et al*., 1993). This view is consistent with the findings of palynologists Martin (1987) and Colhoun & van de Geer (1988). Martin (1987) used composite pollen cores from the Lachlan River Valley in central NSW (Fig. 1) to demonstrate that in the mid-to-late Miocene the vegetation changed from rain forest to a fire-adapted forest possibly dominated by *Eucalyptus*, and that this transition was associated with numerous charcoal particles (Fig. 9). This vegetation change was believed to have been driven by drier Australian climates associated with the formation of the Antarctic ice cap. The long pollen core from Darwin Crater in southwest Tasmania (Figs 1, 9), although imperfectly dated, is thought to span five glacial–interglacial cycles; charcoal and *Eucalyptus* occur throughout the core. It demonstrates that fire caused by natural agencies has been an important component of this environment for over 0·5 million years (Colhoun & van de Geer, 1988). The Darwin Crater core shows that at the time of known Aboriginal colonization of Tasmania (about 35000 BP (Cosgrove, 1989)) there is no evidence of a massive increase in burning or major contraction of rain forest. Considering Darwin Crater, Jackson (1998) has speculated that the increase in charcoal and decrease in the pollen of rain forest taxa in the penultimate glacial, 160000–180000 BP, might reflect the impact of Aboriginal landscape burning. He advances this view despite the lack of archaeological evidence of such early human colonization of Tasmania. In this context, Anderson's (1994) comments on the ODP 820 cores are particularly pertinent. He notes that 'where it is asserted that palynological data document prearchaeological evidence of occupation the argument loses plausibility in proportion to its scale; extensive proxy suggestions of human activity, without any direct evidence, indicates rather the operation of natural agencies'.

That Aboriginal landscape burning was responsible for dramatic changes to the distribution of rain forest throughout Australia is not consistent with pollen evidence from the Pleistocene–Holocene boundary. There is no evidence that burning prohibited the expansion of rain forest in the early Holocene when climates ameliorated (Kershaw 1976; Clark, 1983; Dodson, Greenwood & Jones, 1986; Macphail, 1993). However, evidence from the Atherton Tablelands (Fig. 1) suggests that burning may have controlled the local expansion of rain forest. Data from six palynological cores in a zone with a 13-km radius show that the arrival of rain forest at any one site ranged over a 3000-yr period (Walker & Chen, 1987). Once initiated, however, the transition to rain forest was relatively rapid (< 1500 yr) with a number of dominant rain forest tree taxa showing exponential population growth (Chen, 1988). Further, fine resolution palynology from one core in the region showed that the establishment of rain forest was associated with a decrease in microscopic charcoal particles (Walker & Chen, 1987). On the basis of macroscopic charcoal evidence, Hopkins *et al*. (1993) suggest that climatic amelioration was primarily responsible for the expansion of rain forest in the early Holocene but accepted, as did Walker & Chen (1987), that fires lit by Aborigines may have influenced the rate of rain forest recolonization.

The depopulation of continental islands in the late Holocene offers another view of the impact of Aboriginal landscape burning. There was no change in floristic composition as inferred by pollen analyses on Kangaroo Island (Australia's third largest island), Flinders Island (Australia's seventh largest island) on the southeast coast of Australia, and Hunter Island, a small island off the northwest coast of Tasmania (Fig. 1), following their abandonment by Aboriginal people in the late Holocene (Hope, 1978, 1999). On both Kangaroo and Hunter Islands there is a marked increase in the concentration of charcoal particles following the assumed departure of Aborigines, a feature which Singh *et al*. (1981) and Hope (1999) interpret as reflecting a change in fire regime from frequent burning to periodic and destructive fire caused by lightning or occasional human visitation. However, on Flinders Island, Ladd, Orchiston & Joyce (1992) found that the mid-Holocene departure of Aborigines resulted in no detectable change in the production of microscopic charcoal particles. Clark (1983) attributes the lack of a change in the vegetation on Kangaroo Island and Hunter Island as merely reflecting an inability of pollen analysis to detect a subtle response of fire-adapted vegetation. Although there may have been no floristic change, Hope & Kirkpatrick (1988) suggest that there was a change in vegetation structure.

Head (1989) notes that most arguments concerning Aboriginal landscape burning assume a constant impact with little allowance for changes in the impact of burning in response to climate change and variations in Aboriginal populations, especially a possible population increase in the late-Holocene (Lourandos, 1983; Ross, 1985). Head (1989) cites several examples where Aboriginal landscape burning is thought either to complement or to oppose the direction of vegetation change under the prevailing Holocene climates (Macphail, 1980, 1984; Kershaw, 1983; Macphail & Colhoun, 1985). The difficulty with this analysis is that it is inherently circular because vegetation is used to infer climate as well as being assumed to reflect Aboriginal landscape burning (Head, 1996). Recent research from northeastern Tasmania suggests that vegetation changes during the Holocene were complex and locally variable, and that in consequence generalized climatic signals are difficult to identify (Thomas & Kirkpatrick, 1996). Certainly, the response of vegetation to changed fire regimes in the contemporary environment varies spatially, although the causes of this variability are not obvious (e.g. Podger *et al*., 1988; Bowman & Panton, 1993*a*).

Head (1989) notes that pollen evidence demonstrates a change of fire regime following the colonization of Australia by Europeans, although the direction of this change is also inconsistent. For instance, Gell, Stuart & Smith (1993) have shown that the arrival of Europeans in the Delegate River catchment in southeastern Victoria (Fig. 1) caused a massive increase in charcoal which only subsided once fire control measures were instituted in the 1940*s*. Similarly, Boon & Dodson (1992) also found a marked increase in charcoal particles associated with severe fires about 50 yr after European colonization of the landscapes surrounding Lake Curlip in east Gippsland (Fig. 1). On the other hand, Dodson *et al*. (1993*a*) demonstrate a decrease in microscopic charcoal following European colonization for two sites on the southeast coast of New South Wales. These inconsistent trends may be unrelated to changes in fire regime, instead reflecting the confounding influence of other ecological changes that followed European colonization, such as the introduction of weeds and animals, land clearance and soil erosion (Boon & Dodson, 1992; Horton, 1982; Head, 1989; Dodson *et al*., 1993*a*; Hope, 1999). Nonetheless, as has been previously noted, ecological research has demonstrated that the same vegetation type may expand or contract depending on local environmental conditions. Clearly the ecological context of pollen cores requires considerable thought before attributing any pattern of pollen or charcoal abundance to changes in fire frequency associated with European colonization.

A serious problem with the vast majority of Quaternary palaeoecological studies is that they are strongly biased against arid and semi-arid environments (Dodson, 1989). In consequence, remarkably little is known about the effect of Aborigines across most of the Australian continent (Head, 1989). Although Kershaw (1985) suggests that it is possible to extrapolate findings on the impact of Aboriginal landscape burning from the humid tropics (e.g. Atherton Tablelands) to the monsoon tropics, this is probably unjustified given that these environments are fundamentally different (Ash, 1983). The only published dry land pollen interpretation for monsoonal Australia suggests that burning may have locally influenced vegetation surrounding a coastal swamp on Groote Eylandt (Fig. 1) in the late Holocene but that the effect was minor (Shulmeister, 1992). In the light of this impoverished palaeoecological record, for monsoonal Australia radiocarbon dates of abandoned Orange-footed Scrubfowl (*Megapodius freycinet*) nests have importance as a palaeoecological marker of rain forest retreat. Scrubfowl are ground-dwelling birds that can only construct nests in rain forest habitats (Bowman, Woinarski & Russell-Smith, 1994*a*). Therefore, the occurrence of abandoned mounds in savanna is evidence of rain forest retreat. A positive correlation of distance from rain forest patches and radiocarbon ages of abandoned nests from one locality on Melville Island led Stocker (1971) to hypothesize that the rain forests had gradually retreated in response to climate change, severe tropical storms (known in Australia as 'cyclones'), and/or Aboriginal landscape burning during the Holocene. Subsequent detailed research has shown that the boundary retreat of monsoon forest in the late Holocene is best explained by the impact of cyclones and fires (Bowman, Panton & Head 1999). However, Bowman *et al.* (1999) note that it is not clear that fires in cyclone debris were intentionally started by Aborigines. Russell-Smith (1985) accounted for the retreat of monsoon rain forest at a site within the last 100 years as being caused by increased fire severity associated with the arrival of Europeans and impacts of feral water buffalo (*Bubalus bubalis*).

Currently, it is impossible conclusively to demonstrate the effects of Aboriginal landscape burning in the prehistoric past given the vague time frames available to understand Aboriginal demographics such as settlement patterns and waves of colonization. More problematic is an inherent circularity concerning cause and effect of climatic change vegetation change, and burning through the late Quaternary period (Clark, 1983; Ladd, 1988; Head, 1989). Clearly, peaks of microscopic charcoal particles in pollen cores cannot be treated as an unambiguous indicator of Aboriginal landscape burning (Clark, 1983). Indeed, Horton (1982) believes the inconsistent charcoal-particle response in pollen cores to the presumed presence or absence of Aborigines demonstrates that microscopic charcoal particles cannot resolve the effect of Aboriginal landscape burning on the environment. To date, this criticism has not been rebuffed. The palaeoecological impacts of Aboriginal burning may never be possible to determine because 'it is impossible to hold all other variables constant' (Head, 1989). There is little doubt that because of these serious limitations this aspect of Australian palaeoecology has been so contentious.

4. *Megafaunal extinction and Aboriginal landscape burning: mechanism or myth?*

The extinction of a diverse marsupial fauna with body weights in excess of 10 kg (Flannery, 1990*a*) is as vexing a problem in Australian palaeoecology as is the impact of Aboriginal burning (Horton, 1980). Indeed, the extinction of the megafauna and burning have become conflated (Merrilees, 1968; Jones, 1973, 1979; Flannery, 1990*a*, 1994).

What caused the extinction of the megafauna is intractable because there is neither an agreed time frame for the extinction nor for the arrival of humans (Calaby, 1971,1976; Jones, 1975; Horton, 1980; Flannery, 1990*a*; Wright, 1990; Webb 1998). Megafaunal remains are extremely scarce in Australia, and there is uncertainty concerning the accuracy of radiocarbon dates for the few fossil deposits. Indeed, Grayson (1990) notes the Australian chronology for megafaunal extinction is not weak but effectively 'nonexistent'. Some authors suggest that climate change may have been the primary cause of the megafaunal extinction (Calaby, 1976; Horton, 1977, 1984; Main, 1978; Archer, 1984), but this is inconsistent with the megafauna having survived numerous glacial–interglacial cycles thought to have been of similar severity to the last glacial (White & O'Connell, 1979; Martin, 1984; Wright, 1986*b*; Kershaw, 1989). Although archaeological material has been found associated with megafaunal remains, there is no clear-cut evidence of human predation (Gillespie *et al.*, 1978; Archer, 1984; Gorecki *et al.*, 1984; Dodson *et al.*, 1993*b*). In marked contrast to northern hemisphere megafaunal extinctions, no killing grounds and tools designed to kill large animals have been found in Australia (Owen-Smith, 1989). It is unclear if this lack of evidence is real or is a consequence of the lack of suitable environments for the long-term preservation of kill sites in Australia (Kohen, 1995). Contemporary ethnographic and ecological evidence demonstrates that Aborigines quickly incorporated introduced, horned and therefore potentially dangerous, feral megafauna such as buffalo and cattle into their diet. However, the Aborigines were unable rapidly to exterminate these introduced large herbivores with their comparatively refined late Holocene and post-European contact tool kit (Calaby, 1971; White & O'Connell, 1979; Bowman, 1993*b*; Kohen, 1995). Significantly, feral animal control operations have shown that trained hunters using helicopters and high-powered rifles are unable to exterminate large animals in the vast landscapes of northern Australia, particularly when populations fall to low densities (Bowman, 1991; Boulton & Freeland, 1991; Choquenot & Bowman, 1998).

Because climate change and Aboriginal hunting do not seem able to explain the extinction of the marsupials, some authors have suggested that habitat modification associated with Aboriginal landscape burning may have been an additional factor in their demise (Merrilees, 1968; Jones, 1968, 1973; 1979; Archer, 1984). This is extremely difficult to substantiate because there is no palaeoecological evidence that megafauna habitats adversely changed during the Pleistocene (Dodson, 1989). Even if there were such evidence, it would not be possible to demonstrate that these changes were the work of Aborigines (Horton, 1980). It is possible that Aboriginal burning may have created habitats that favoured the survival of large herbivores (Horton, 1977, 1984).

Little has changed in our understanding of megafaunal extinction since Jones (1975) pointed out that more needs to be learnt about 'long term climatic and environmental trends since the Tertiary, the ecologies of both extinct and extant forms, the chronologies of extinctions including those which occurred in the Tertiary and early Pleistocene, and if possible, stratigraphic demonstration of man's relationship with all elements of the late Pleistocene fauna'. However, the debate has been stimulated by the recent publication of a hypothesis by the palaeontologist Flannery (1990*a*, *b*, 1994) which links megafaunal extinction, Aboriginal burning, and the extinction of small mammals following European colonization. Even though Flannery (1990*a*) acknowledged that there is 'no satisfactory resolution as to the timing of Pleistocene faunal extinctions in Australia' he was not deterred from advocating and, subsequently, publicly championing (Flannery, 1994) this hypothesis, described by Head (1995) as being 'courageous' because it is so dependent on a specific unproven timetable of human colonization and megafaunal extinction. Head (1995) notes that one site of human occupation too old, or a megafauna site too young, that is unambiguously dated 'can blow it apart'.

Flannery's hypothesis (1990*a*, 1994) assumes the following chain of events. Initially, Aboriginal colonization in the Pleistocene resulted in an almost immediate extermination of the megafauna, a so-called hunting 'blitzkrieg'. The loss of the megafauna resulted in enormous build-up of fuels and intense fires, which eliminated fire-sensitive plant species. The Aborigines learnt to contain the fires by pre-emptive regular burning, thereby producing a habitat mosaic. Such a habitat mosaic is thought to be critical for the survival of small mammals and prior to Aboriginal colonization it was maintained by megafaunal herbivory. The arrival of Europeans and consequent cessation of patchy burning by Aborigines resulted in the mass extinction of small mammals because their habitat was homogenized by broad-scale wildfires. In a nutshell, although delayed by skilful Aboriginal landscape burning, the mammal extinctions that occurred following European colonization were a direct consequence of the anthropogenic Pleistocene megafaunal extermination. The novelty of this hypothesis is that Flannery made a connection between megafaunal extinction and the role of Aboriginal landscape burning in maintaining small mammal habitats. Formerly, Owen-Smith (1989) had argued that burning might simulate the role of megaherbivores in maintaining small mammal habitats in African savannas. Schule (1992) emphasized a linkage between over-hunting of megaherbivores and burning in inducing habitat changes, which, he suggested, could have triggered Pleistocene climate change.

Apart from the serious chronological and palaeoecological problems already stated, there are a number of ecological reasons to doubt Flannery's hypothesis. As previously discussed, available field evidence does not support the hypothesis that the cessation of mosaic burning primarily caused the extinction of small mammal species in central Australia (Morton, 1990*a*; Short & Turner, 1994), although there is evidence that burning may have locally advantaged some mammals (Johnson, 1980; Lundie-Jenkins, 1993; Vernes *et al*., 1995). Field experiments show that fire and megaherbivory are not ecologically analogous (Leigh & Holgate, 1979) and there is evidence that grazing may increase the intensity of fires in some woody vegetation types (Hobbs, 1996). In any case, the long-term pollen cores which show prehistoric impacts of fire on vegetation and which are central to Flannery's argument were collected near forested regions on the east coast of Australia. The loss of small mammals there is minor, and the loss of mammal species is best explained by habitat clearance by Europeans. Disjunct populations of arid-zone plant species such as the shrub *Acacia aneura* and hummock grasses in the genus *Triodia* demonstrate that environmental change has resulted in complex distribution patterns apparently related to long-term climatic change rather than the alleged impact of megafaunal extinction and subsequent Aboriginal landscape burning (Jacobs, 1982; Maslin & Hopper, 1982; Bowman,

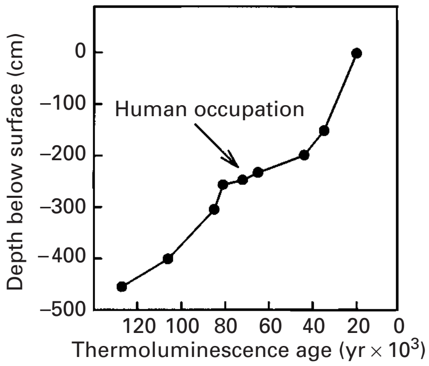

Figure 10. Relationship between sediment depth and sediment age of from a well-dated archaeological site in Kakadu National Park. Human occupation is indicated by the first occurrence of archaeological artefacts. The slope of the line between two consecutive samples indicates the rate of sedimentation. Adapted from Roberts *et al.* (1990).

Panton & Latz, 1995). Further, although fire regimes have changed in northern Australia, thus far there have been no corresponding losses of small mammals (Morton 1990*a*). The survival of small mammals in northern Australia led Bowman (1991) to query the reality of Flannery's (1990*a*) 'unifying predictive hypothesis'.

The cause and consequences of the extinction of the marsupial megafauna requires much more research, but sparse available data do not support the hypothesis that the colonizing Aborigines eliminated the megafauna in a 'blitzkrieg'. It is likely that the extinctions occurred gradually (White & O'Connell, 1979; Wright 1986*b*; Kohen, 1995). Like the extinction of large Pleistocene animals elsewhere in the world, the demise of the marsupial megafauna was probably a response to many factors associated with human colonization, climate change and habitat changes (White & O'Connell, 1979; Owen-Smith, 1992; Choquenot & Bowman, 1998).

5. *Did Aboriginal landscape burning trigger geomorphological instability?*

Some geomorphologists, archaeologists and palynologists have suggested that burning may have triggered soil erosion (Tindale, 1959; Hughes & Sullivan, 1981; Jones, 1985; Kershaw, 1994*a*). If this were the case, then this impact should be recorded in the sedimentary record, but it is not.

Jones (1985) hypothesized that the initial impact of Aboriginal burning may be preserved in archaeological deposits in Kakadu National Park. However, the excavation of an archaeological site in a 4·5-m deep sandsheet in which evidence of human occupation occurs abruptly at 2·6 m below the surface reveals that the rate of sediment accumulation was not influenced in any way by the presence of humans (Roberts *et al.*, 1990) (Figs 1, 10). Indeed, at the catchment scale there is no evidence of increased erosion following the arrival of humans in the Kakadu region (Nanson, East & Roberts, 1993; Russell-Smith *et al.*, 1997). Nonetheless, what triggered the late Quaternary erosion of sandstone plateaux in northern Australia is not clear (Nanson *et al.*, 1993). Over the last 100 million years, such plateaux are thought to have had extraordinarily low rates of landscape denudation of approx. 0·5 m per million years (Nott, 1995).

There has been a productive debate concerning human-induced erosion in southeastern Australia during the Holocene. Hughes & Sullivan (1981) interpreted the clustering of late Holocene alluvial sediments in southeastern New South Wales streams as a consequence of increased burning associated with assumed, albeit unproven (Lourandos, 1983; Ross, 1985; Head, 1989), expanding Aboriginal populations. Young, Nanson & Bryant (1986) rejected this interpretation, arguing that the clustering was an artefact of the breakdown of old carbon by weathering and localized erosion events. A reanalysis of published data led Proser (1987) to conclude that there was continuous deposition of alluvial sediments in the highlands of southeastern Australia throughout the Holocene. Therefore he rejected the hypothesis that increased Aboriginal landscape burning triggered erosion in the late Holocene. Boon & Dodson (1992) and Dodson *et al.* (1993*a*) demonstrate that frequent burning prior to European colonization resulted in less erosion than occurred following European colonization when the frequency of fires declined.

Wasson (1986) reviewed the possible geomorphological effects of Aboriginal burning on central Australian dunefields in the late Pleistocene and Holocene. He concluded that climate was the driving force behind dune building, and that Aborigines had, at most, a localized effect on rates of aeolian erosion. This is consistent with Thomas & Kirkpatrick's (1996) finding that in northeastern Tasmania intensive use of a coastal site by Aborigines in the mid Holocene may have temporarily increased localized aeolian erosion of adjacent coastal dunes.

6. *Aboriginal landscape burning: an evolutionary force?*

A widely accepted hypothesis is that Aboriginal burning played an important role in the range extensions and diversification of fire-adapted species, particularly in the genus *Eucalyptus* (Kershaw, 1981; Singh *et al.*, 1981; Gillison, 1983; Janzen, 1988; Hill, 1994). For example, Kershaw (1981) argued that the 'great variation shown within species and species groups would support a relatively recent radiation and massive extension of range which may have been linked with the development of open eucalypt communities' and that 'the most tenable explanation of why changes occurred at this particular time is that aboriginal man encouraged fire and its effects'. The contrary view is that the great diversity and superb adaptations to withstanding periodic fires (Jackson, 1968; Ashton, 1981) of much of the non-rain forest vegetation is the consequence of a long history of burning that preceded human occupation (Jacobs, 1956; Gill, 1973; Mount, 1979; Nix, 1982; Martin, 1987; Bowman, Woinarski & Menkhorst, 1994*b*).

The idea that fire-adapted vegetation radiated in the late Pleistocene is based on pollen evidence from long cores (e.g. Singh *et al.*, 1981). Considering biogeographic patterns, fossil evidence, and phylogenetic relationships as inferred by morphology and DNA, Ladiges (1997) concluded that *Eucalyptus* and related genera are an ancient group pre-dating the separation of New Zealand and New Caledonia from the Australian plate some 60 million years ago. She argues that *Eucalyptus* is a paraphyletic clade and that diversification has been primarily because of vicariant speciation. In her opinion, the role of hybridization in forming new species is equivocal. Most individual species of *Eucalyptus* have narrow climatic ranges. For example, Hughes, Crawsey & Westoby (1996) found that 67% of *Eucalyptus* species which occur on the Australian mainland and the island of Tasmania have geographic distributions where the mean annual temperature range is < 5 °C, and that 25% of these species have a thermal geographic range of < 1 °C (Fig. 11). Hughes *et al.* (1996) suggest that such narrow thermal ranges of *Eucalyptus* spp. make the genus susceptible to climate change. If so, then it also suggests a long evolutionary history, which contributed to the narrow specialization of over 800 tree species (Hughes *et al.* 1996).

A feature of *Eucalyptus* communities is structural and floristic diversity throughout the Australian continent (Wardell-Johnson *et al.*, 1997) with a corresponding diversity of vertebrate and invertebrate herbivores (Landsberg & Cork, 1997). It is improbable that the diversification and geographic patterning of the *Eucalyptus* biota could have arisen during the period of human colonization.

The occurrence of small patches (often only several hectares in extent) of monsoon rain forests in vast tracts of *Eucalyptus* savanna is also seen by some as evidence of burning having had a massive impact. The numerous isolated patches of monsoon forests which often contain rare or disjunct plant species can be interpreted as fragments of a formally continuous forest that was replaced by fire-adapted *Eucalyptus* savanna (e.g. Gillison, 1983; Russell-Smith, 1991; Russell-Smith *et al.*, 1993). Notwithstanding, there is evidence that many monsoon rain forest species are well dispersed and actively colonize Holocene landforms (Bowman *et al.*, 1990; Russell-Smith & Lee, 1992).

There are no fossil data available to determine the timing of a putative transition from rain forest to *Eucalyptus*-dominated vegetation in northern Australia. The only known Tertiary plant macrofossil deposit in northern Australia is considered to be representative of seasonally dry vegetation that is neither savanna nor rain forest and for which no modern analogues exist (Pole & Bowman, 1996). The diversity of monsoon savanna tropical tree species (Taylor & Dunlop, 1985), the strong correlation of savanna tree species distributions with specific environmental conditions (Bowman *et al.*, 1994*b*), coordinated sequential flowering times of trees (Bowman, Wilson & Woinarski, 1991) and the great diversity of savanna ant assemblages relative to monsoon rain forest ant assemblages (Andersen, 1991; Reichel & Andersen, 1996) all strongly point to the great antiquity of these systems. Furthermore, like monsoon rain forests, the savannas also contain rare species, disjunct populations, and species with enormous geographic ranges (Bowman *et al.*, 1994*b*). For example *Eucalyptus tetrodonta*, which has a poorly dispersed small spherical seed of about 1 mg in weight, occurs in a series of large isolated tracts from Cape York to Cape Leveque in Western Australia covering a distance of over 2000 km (Chippendale & Wolf, 1981) (Fig. 1). Such a distribution pattern is most unlikely to have arisen in a short time. For these reasons, Bowman *et al.* (1994*b*) and Bowman & Panton (1993*a*) reject the hypothesis that the diversification and geographic range of monsoon *Eucalyptus* savanna biota could have been a response to Aboriginal landscape burning occurring over one glacial–interglacial cycle.

Vertebrate biogeography also suggests that savannas and *Eucalyptus* communities are of great antiquity (Archer *et al.*, 1989). At Riversleigh in the Gulf of Carpentaria (Fig. 1), a complex rain-forest mammal fossil assemblage gave way to grazers in the late Tertiary. The modern vertebrate assemblage in monsoonal northern Australia is characterized by savanna specialists with few rain-forest specialists (Bowman & Woinarski, 1994). However, Smith & Ganzhorn (1996) speculate that loss of large tracts of monsoon rain forest because of Aboriginal burning in the Pleistocene may have caused arboreal mammals specialized to the habitat to have become locally or globally extinct.

In summary, the available evidence does not support the hypothesis that Aboriginal burning caused the evolutionary diversification of the Australian biota. A possible evolutionary impact of Aboriginal burning may have been the extinction of some fire-sensitive species of plants, and extinction of animals dependent on large tracts of infrequently burnt habitat, particularly during periods of climatic stress (Nix, 1982; Macphail, Jordon & Hill, 1993). Aboriginal burning probably extended the range of fire-adapted species, especially at the expense of rain forest vegetation (Jackson, 1968; Smith & Guyer, 1983).

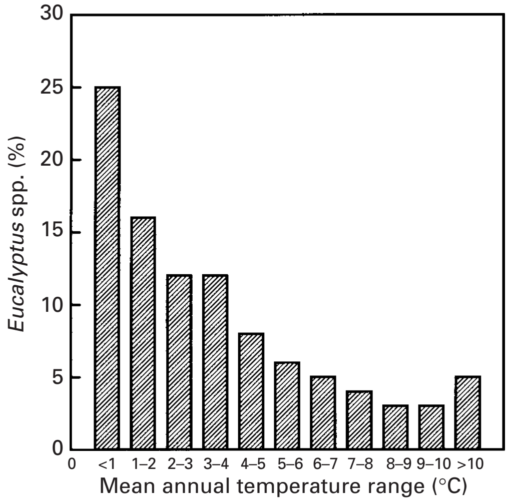

Figure 11. Proportion of *Eucalyptus* spp. ($n = 819$) in 12 categories of geographic thermal ranges as determined by the range (in °C) of the estimated mean annual temperature of all sites where a given species occurs. Adapted from Hughes *et al.* (1996).

V. GENERAL CONCLUSIONS

Arguments concerning the impact of Aboriginal burning focus on two disparate temporal perspectives. The first concerns the environmental consequences of the introduction into Australia of a new ignition source: *Homo sapiens*. The second temporal perspective concerns the role of intentional burning by Aborigines in the maintenance of biodiversity in modern Australia. The initial impact of Aboriginal burning is a fascinating and fundamental anthropological problem (Stewart, 1955; Tindale, 1959; Jones, 1968) which must await far more research before reasonable conclusions can be drawn. However, we will never know if the first Aboriginal colonists used fire skilfully to achieve specific ends, or used fire in a crude and largely uncontrolled way. Given that the human colonists were genetically and culturally different from modern Aborigines, we should not extrapolate the impacts of the first colonists to their distant descendants. To do so would be akin to inferring the impacts of upper Palaeolithic Europeans from those of their Neanderthal congeners.

The debate concerning landscape burning has focused on putative initial impacts of Aborigines in the analytically intractable, prehistoric past, rather than on their effect in the measurable present. This conflation of prehistoric impacts and contemporary land-management issues can be traced to Jones' (1969) rhetorical remark in the conclusion of his classic paper in which he coined the term 'fire-stick farming'. Jones (1969) wrote 'what do we want to conserve? We have a choice. Do we want to conserve the environment as it was in 1788, or do we yearn for an environment without man, as it might have been 30000 or more years ago?' This is a *non sequitur*. Our responsibility to conserve extant biodiversity is clear. Even if we were able to know all the details of the prehuman Australian landscape, clearly it can never be recreated. Obviously, in order fully to understand the effect of Aboriginal burning an appreciation of environmental change across a range of temporal scales is required (Head, 1989; Thomas, 1993). However, given the importance of fire in Australian land management, emphasis must be placed on the present. Attribution of alleged destructive impacts following the arrival of Aborigines in Australia deflects attention from pressing conservation problems. Indeed, vague, speculative palaeoecological arguments can be used for mischievous political purposes in the intense ongoing debates about the conservation and development of Australia's natural resources (Head, 1989; Horton, 1990; Langton, 1998). However, Jones' (1969) rhetorical remarks are based on his profound realization that European land managers must choose what sort of 'natural' landscapes they want, given the backdrop of an extraordinarily long period of Aboriginal burning.

Although there remain great uncertainties and gaps in knowledge, the available evidence leaves little doubt that Aboriginal burning was skilful, and was central to the maintenance of the landscapes colonized by Europeans in the 19th century. However, it is unclear if Aborigines had a more systematic and predictive ecological knowledge of the consequences of their use of fire. What is required is an advance from the poetic concept of fire-stick farming (Jones, 1969) to a coherent scientific analysis of Aboriginal burning that can be used to buttress land-management prescriptions. The ecological basis for the use of burning in landscape management was not widely appreciated until the 1970*s* (Luke & McArthur, 1978; Gill, Groves & Noble, 1981), and there remains much to understand. In environments where Aborigines maintain close links with the land, there is an urgent need directly to involve Aboriginal people, especially the older ones, in collaborative research on the fire ecology of various ecosystems.

In landscapes that have been depopulated of Aboriginal people and which have suffered drastic environmental transformations following European colonization, teasing out the ecological role of Aboriginal burning is extremely difficult (Kitchener *et al.*, 1980; Pulsford *et al.*, 1993). Palaeoecological studies such as dendrochronology, palynology and charcoal particle analysis and ethnohistorical resources can de used to frame ecological hypotheses, as was ably demonstrated by Burrows *et al.* (1995). Where practical, these hypotheses require testing using the standard battery of ecological tools such as field experimentation and environmental correlation, although to date this has not been rigorously pursued. It will also be required to learn how to control fires in order to maintain particular vegetation types. The studies undertaken by Marsden-Smedley and Catchpole (1995*a*, *b*) in southwest

Tasmania are an excellent example of such applied research.

It is wrongheaded to ignore the ecological impact of a long history of Aboriginal burning. In Australia ecologists cannot retreat to the 'wilderness' to study an archetype of nature because the 'wilderness' has long included people.

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