Flammable Australia

The Fire Regimes and Biodiversity of a Continent

Edited by

ROSS A. BRADSTOCK
New South Wales National Parks and Wildlife Service

JANN E. WILLIAMS
Royal Melbourne Institute of Technology University

MALCOLM A. GILL
CSIRO Plant Industry

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A history of fire in Australia

A. PETER KERSHAW, JAMES S. CLARK, A. MALCOLM GILL AND DONNA M. D'COSTA

Abstract
Over the last 20 years, the counting of charcoal in association with pollen in the construction of palaeoenvironmental records from swamp, lake and marine sediments has become routine. This has provided a substantial, although methodologically variable and geographically biased, data set with which to examine the history of burning on the Australian continent. Two generalised records from southeastern Australia demonstrate a general increase in burning within the later part of the Tertiary period in line with reduced precipitation, increased climatic variability and development or expansion of sclerophyll forest and heath vegetation. The one continuous record of vegetation and burning from the early part of the Quaternary suggests that this period may have experienced relatively stable environmental conditions. Increased fire activity is evident in the majority of records extending through at least the last glacial/interglacial cycle, particularly during drier glacials and during times of major climate change. A focus on southeastern Australia for the last 11 000 years (11 ka), a place and period containing the bulk of charcoal records, indicates high fire activity over the last few thousand years, with a major peak coinciding with the early phase of European settlement followed by reduction within recent decades to Early Holocene levels. It is demonstrated that climate has exerted the major control over both fire activity and vegetation change. There is a notable increase in fire activity centred on 40 ka before present (BP) which, in the absence of a major climate change around this time, is considered to most likely indicate early Aboriginal burning. The impact on the vegetation was largely to accelerate existing trends rather than cause a wholescale landscape change. It is difficult to separate the effects of climate and human-induced burning subsequent to this time until the arrival of Europeans.

Introduction

The first systematic examination of evidence for the role of fire in the historical development and maintenance of Australian vegetation was presented in *Fire and the Australian Biota* (Gill *et al.* 1981). The evidence was minimal. Kemp (1981) in her review of pre-Quaternary fire speculated on the vexed question of the extent to which the geological material 'fusain' was a product of biomass burning and on likely changes in fire activity through the Tertiary period based on vegetation/climate patterns. Most direct evidence for fire within the Cainozoic period derived from the brown coals of Victoria with the general acceptance that fusinite was largely charcoal derived from the burning of swamp vegetation, with lightning and spontaneous combustion being the major ignition agents. No data were available to determine whether or not these fires had any long-term effect on the character of the vegetation. In lieu of any direct fire–vegetation relationships, Kemp surmised that burning activity would have increased during the Tertiary and Quaternary periods in response to increasingly dry and variable climatic conditions.

Singh *et al.* (1981) focussed their paper 'Quaternary vegetation and fire history in Australia' on three recently produced pollen records incorporating measures of charcoal particles as direct evidence of past fires. All three records demonstrated some relationship between fire activity and climatic conditions but major features of the records related to the presumed impact of Aboriginal people on fire regimes and sustained vegetation change. The long record of

Lake George, near Canberra, subsequently extended and refined by Singh and Geissler (1985), provided what was considered to be a continuous record through the last four glacial/interglacial cycles, about the last 400 000 years (400 ka). The earlier part of this record showed a pattern of significant fire activity only during wetter and warmer interglacials which were dominated by Casuarinaceae with minor rainforest elements. It was considered that the cooler, drier glacials, dominated by herbaceous vegetation, were too open to support regular fires. This pattern changed at the beginning of stage 5 (the last interglacial, *c.* 125–130 ka BP – before present) with higher and more continuous burning. This was considered to be a result of an additional ignition source, the activities of Aboriginal people. There was a substantial replacement of Casuarinaceae by eucalypts and a reduction in rainforest elements during the last and present (Holocene) interglacials, and a general sustained increase in myrtaceous shrubs. The maintenance of high burning levels during the last glacial period was considered to be the result of an increase in sclerophyllous vegetation combined with persistent Aboriginal burning. Highest burning levels for the whole diagram were achieved near the top of the record, considered to be the result of activities of early European colonists, before a sharp decrease in recent years representing the implementation of a fire-exclusion policy.

A record from Lynch's Crater, from the Atherton Tableland, in the humid tropics region of northeast Queensland, covered the last glacial cycle, with complex rainforest dominant during the last interglacial under high precipitation levels and araucarian rainforest together with some sclerophyll forest or woodland prevalent during the first part of the last glacial period (Singh *et al.* 1981). Relatively low charcoal levels suggested infrequent burning, although fire activity was most evident during phases with higher sclerophyll representation, and also at times of major climate and vegetation change, presumably as a result of general environmental instability. A substantial increase in burning occurred around 38 ka BP, considered to be responsible for a gradual replacement, between 38 and 26 ka BP, of 'fire sensitive' araucarian forest by sclerophyll communities, co-dominated by Casuarinaceae and *Eucalyptus,* and also for the extinction of a previously conspicuous member of swamp and riverine communities, the conifer *Dacrydium.* Aboriginal burning was hypothesised to be the major cause of change largely because it did not correspond with any time of known major climate change. Araucarian forest is now restricted, in northeastern Australia, to small, isolated and relatively fire-protected patches. High, although variable, burning levels have been maintained subsequently except for the mid Holocene when high precipitation allowed a re-expansion of complex rainforest within the area.

The much shorter sequence from Lashmar's Lagoon, on Kangaroo Island, South Australia, covering much of the Holocene period, showed consistently low charcoal values, suggesting low fire activity within surrounding *Casuarina stricta* woodlands, until there was some increase in burning around 5 ka BP, considered to be the result of a regional decrease in precipitation (Singh *et al.* 1981). Shortly afterwards, about 4.8 ka BP, there was a rapid replacement of the *Casuarina* woodland by eucalypt woodland, caused by the drier climate but probably facilitated by a short phase of higher burning activity indicated by a charcoal peak. Around 2.5 ka BP there was a major increase in charcoal particles, sustained until after the arrival of European people, but without any concomitant response in the vegetation. It was considered that this charcoal increase was the result of a shift from a regular low- intensity burning pattern maintained by Aborigines, to a pattern of infrequent but high-intensity fires with the disappearance of people from the island.

These three Quaternary records have been prominent in debate about the role of fire, and particularly the impact of people, in the evolution and dynamics of Australian vegetation for almost the last 20 years. Virtually all interpretations have been criticised. Most criticisms have been made on the Lake George record, largely because of the inferred presence of people at least 60 ka earlier than that revealed in the archaeological record (Flood 1995). It has also been proposed that the inferred time-scale is incorrect (Wright 1986) and that the greater 'fire sensitivity' of Casuarinaceae relative to *Eucalyptus* can be questioned (Ladd 1988). The most extreme opposing view to that of Singh *et al.* (1981) was presented by Horton (1982) who considered that Aboriginal people had little effect on existing fire regimes and that the pre-European settlement vegetation cover, as well as the composition and distribution of dependent fauna, would have been the same as it was regardless of whether people had been here or not. Bowman (1998) in the latest review of Aboriginal burning in relation to the Australian biota presents yet another examination of these records and, although he incorporates some more recent studies, is equivocal about the value of past vegetation and fire records for determination of the role of Aboriginal people in the development and maintenance of Australian landscapes.

Perhaps the largest overall problem with the Singh *et al.* (1981) paper was that it provided three stories which, although internally consistent, together appeared to contain major differences with respect to the timing of initial human impact and vegetation responses to fire generated by both natural and human causes. The time gap between the first evidence for inferred human burning at Lake George and Lynch's Crater (i.e. 90 ka) is substantial and, although originally explained by the likelihood that more open vegetation would be most readily settled and transformed by people, this interpretation was unconvincing. Similarly, arguments made for increased charcoal abundance on the grounds of both human presence and absence at different sites reduced the validity of the human-caused burning hypothesis in the minds of a number of critics. The consistency in the three records is that they show a general increase in charcoal through time and change from a less to more fire 'tolerant' vegetation, suggesting that fire has become an increasingly important component of the dynamics of the vegetation within the late Quaternary.

We are now in a position to make a more informed assessment of the nature of the fire record and its relationship to vegetation. There is now a more substantial database of over 100 pollen records with associated charcoal curves and additional information provided by elemental carbon analysis, fire scars on trees and identified soil charcoal. Greater understanding of charcoal–fire and charcoal–pollen relationships has been provided by experimental and fine resolution studies in Australia (R. L. Clark 1982, 1983) and particularly North America (e.g. J. S. Clark 1988; J. S. Clark and Hussey 1996). However, the data, in the main, are still crude both in terms of time resolution and accuracy and are biased towards certain parts of the continent. Following the example set by Singh *et al.* (1981), there is also a lack of consistency in methods of counting and portrayal of charcoal data. Counting methods range from point counting which provides a measure of the area of a microscope slide prepared from a pollen sample covered by charcoal, simple counting of charcoal particles above a certain size (usually 5, 10, 15 or 20 μm), to visual assessment of relative abundance. Quantitative measures of charcoal abundance are displayed variously in the form of concentration (e.g. $cm^2\,cm^{-3}$, $mm^2\,cm^{-3}$, particles cm^{-3}, particles g^{-1}), influx (e.g. $cm^2\,yr^{-1}$, $cm^2\,cm^{-2}\,yr^{-1}$) or as charcoal/pollen concentration or percentage ratios, with the pollen component being total pollen, total dryland pollen or an individual taxon such as *Eucalyptus.* This lack of consistency essentially prohibits the establishment of a quantitative, comparative measure of charcoal abundance and hence fire activity.

In line with the limitations of charcoal data for the determination of fire activity, information provided by pollen for the reconstruction of vegetation is similarly restricted. Of particular concern is our inability to identify pollen taxa to taxonomic levels which allow the recognition of differential responses to individual fires or to fire regimes. Consequently, we generalise the terminology applied to responses of individual species or species groups to higher taxonomic groupings and vegetation types. If communities or taxa are closely associated with high charcoal levels they are considered to be 'fire tolerant' relative to those which

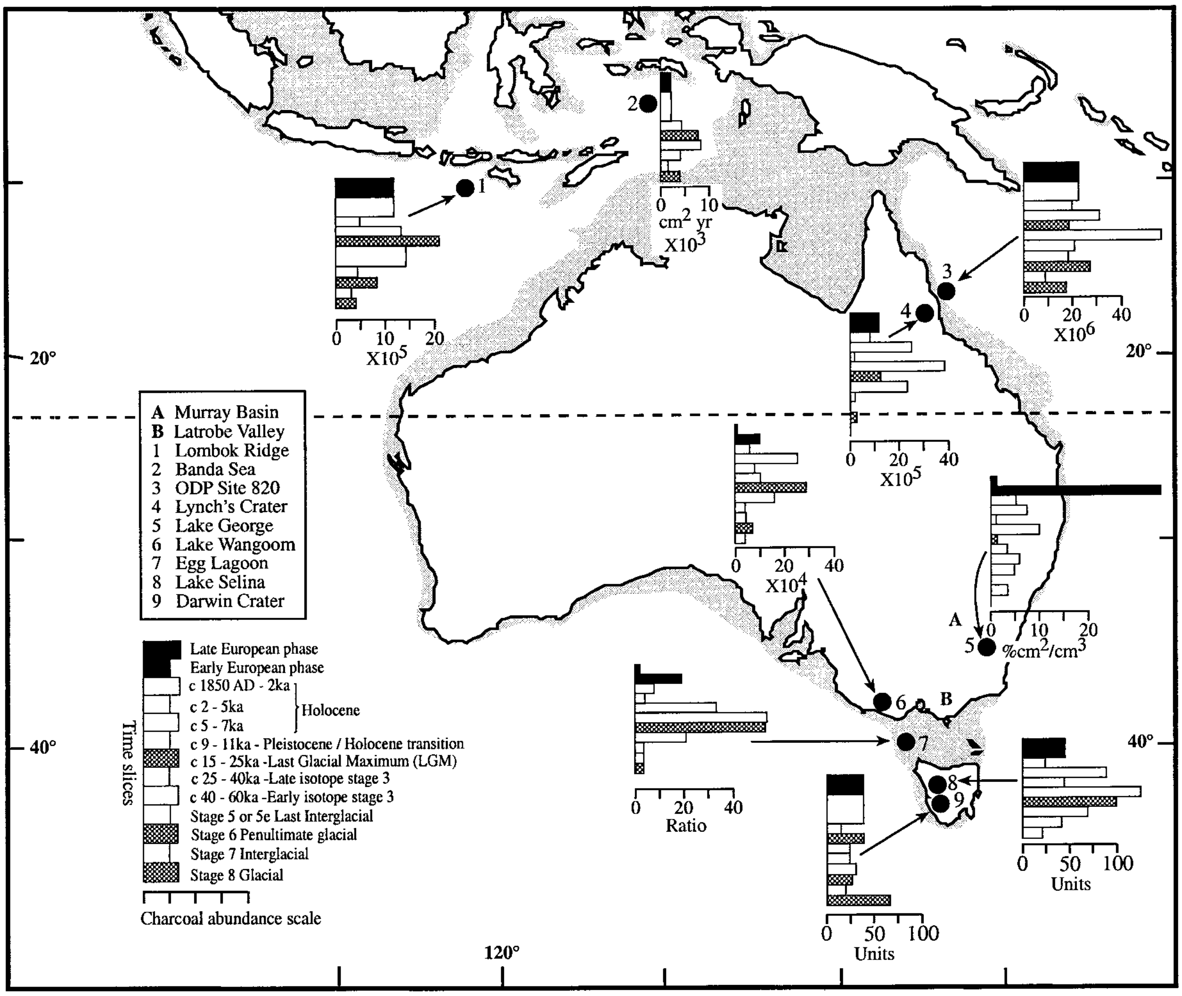

Fig. 1.1. Location of Tertiary and Quaternary sites with long pollen and charcoal records examined in this paper and relative abundance of charcoal for time slices for the Quaternary records. See Table 1.1 for sources and details of the different measures of charcoal.

experience low charcoal levels which are termed 'fire sensitive'.

Pre-Quaternary fire activity

The two major areas in Australia where the composition of vegetation in the Tertiary period has been reconstructed, the Murray River catchment and the Latrobe Valley (Fig. 1.1), have associated charcoal records. These records cover substantial portions of the major period of climate change experienced in Australia, related to the continent's separation from Antarctica in the Eocene, about 40 million years ago (40 Ma BP), followed by its movement into lower latitudes. Although both study areas are in the southeastern part of the continent, they reflect some geographical variation along the present climatic gradient from moist coastal environments to the drier interior.

The generalised record from the Murray catchment (Martin 1990, 1991; Kershaw *et al.* 1994) (Fig. 1.2) shows the predominance of *Nothofagus* pollen,

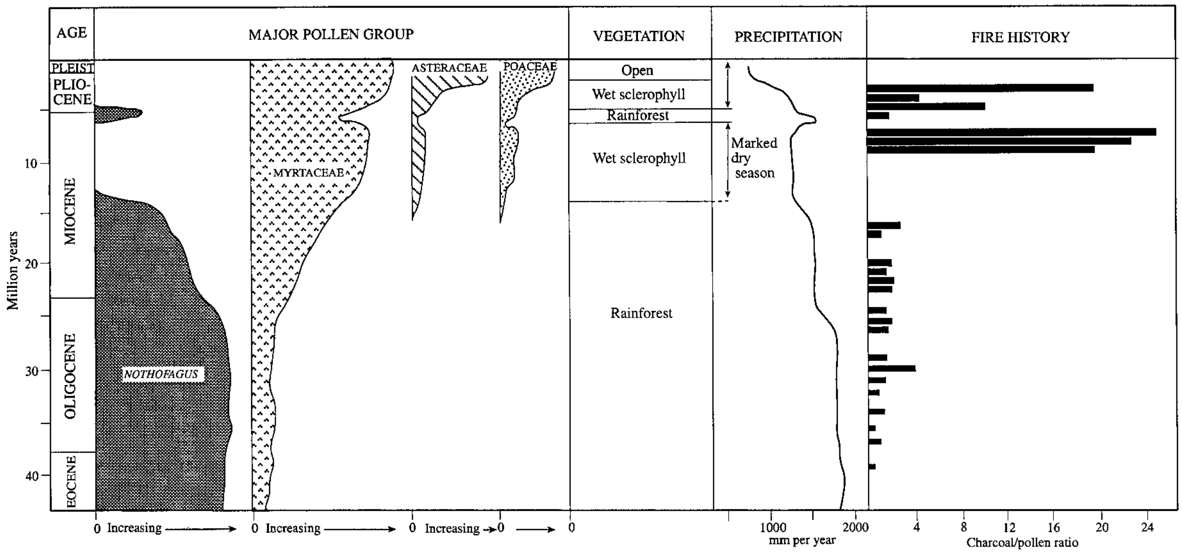

Fig. 1.2. Summary Cainozoic record of pollen and charcoal together with inferred vegetation and precipitation changes from the eastern part of the Murray Basin, N.S.W. Adapted from Martin (1990, 1991).

characteristic of Tertiary rainforest through most of Australia, from the Late Eocene and Oligocene periods. Charcoal levels indicate that fire was present, but probably very infrequent during the Eocene, and that fire activity was somewhat higher during the Oligocene. The steady increase in Myrtaceae from the Late Oligocene to the Early Miocene may indicate some opening of the rainforest canopy or, more likely in the absence of the herbaceous taxa Poaceae and Asteraceae, a change to warmer or more seasonal rainforest types. There is no evidence of an increase in burning during this period. The sharp decline in *Nothofagus* around 15 Ma BP in the Mid Miocene together with the presence of herbaceous taxa certainly indicates a reduction in rainforest and presence of more open canopied vegetation. It is inferred that the vegetation was wet sclerophyll (or tall open) forest dominated by Myrtaceae with a mix of rainforest taxa in the understorey. In the present Australian environment, the canopy of wet sclerophyll forests is dominated everywhere by the non-rainforest genus *Eucalyptus* (Gill and Catling, this volume), but in these fossil assemblages other Myrtaceae, perhaps including genera of present-day rainforest margins such as *Tristania, Tristaniopsis* and *Syncarpia,* were conspicuous. Charcoal levels are very high in the Late Miocene samples and, although charcoal records are not available for Mid Miocene sequences, it may be assumed that high levels were achieved with the development of wet sclerophyll forest as intense fires are associated with this kind of vegetation today. Similar conditions continued through the Pliocene apart from a temporary re-expansion of rainforest during the Early Pliocene when burning was reduced to pre-wet-sclerophyll levels. The very Late Pliocene/Early Pleistocene witnessed a likely further opening of the canopy. The high levels of herbaceous taxa, combined with high values of Myrtaceae and lack of rainforest taxa, suggest the development of open-forest or woodland. Such vegetation types dominate the landscapes of these areas today.

The Murray catchment record provides data that support the proposition of Kemp (1981) that burning would have increased through the later

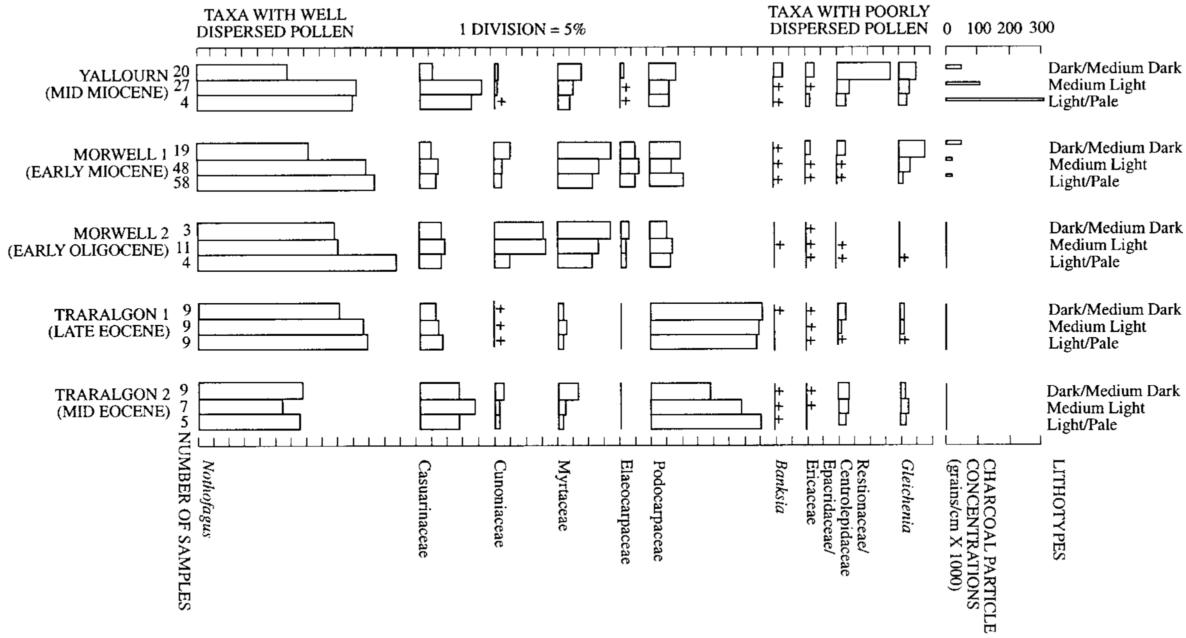

Fig. 1.3. Summary of Cainozoic pollen and charcoal records from the Latrobe Valley coal measures, western Victoria. Adapted from Kershaw *et al.* (1991).

part of the Cainozoic period in response to drier and more variable climatic conditions. There is certainly a good relationship between vegetation, inferred rainfall and charcoal although the record is too generalised to determine the degree to which fire was actively driving vegetation change rather than simply responding to climatically induced change. The suggested presence of wet sclerophyll forest is interesting because, in contemporary conditions, fire is considered essential for the maintenance of a mix of shade-intolerant eucalypts and shade-tolerant rainforest taxa. There is a great deal of speculation on the long-term stability of such communities and whether they can exist in the absence of fire generated in surrounding more open vegetation. The evidence from the Murray catchment is that wet sclerophyll, although different floristically from any vegetation type present today, can be maintained over long periods of time.

The Latrobe Valley provides a similar span of vegetation history to that of the Murray catchment but charcoal data are restricted to sequences derived from Eocene to Miocene coal seams which accumulated as peat on the onshore section of the subsiding Gippsland Basin (Kershaw *et al.* 1991; Sluiter *et al.* 1995). The summary diagram (Fig. 1.3) indicates average pollen and charcoal values for samples from each major coal lithotype group within each coal seam. Although it has been traditionally thought that peat accumulation was largely continuous through the whole period, recent sequence stratigraphic analysis has suggested that phases of coal seam accumulation relate to major global sea-level highs and may only have occupied about 7.5 of the 26 Ma period represented by the coal measures (Holdgate *et al.* 1995). Furthermore, peat accumulation within each seam may have been restricted to sea-level highs of several thousand years duration within fourth-order eustatic cycles (Haq *et al.* 1987). Consequently the record may be very biased towards wetter periods which are most likely to accompany sea-level highs. Lithotype groups have been separated on the diagram because they represent different depositional environments within the coal-forming basin, although the actual nature of these environments is the source of debate.

Original palynological and plant macrofossil interpretation was that there was a lithotype colour gradient from light to dark representing hydroseral succession, initiated by periodic basin subsidence, from open water to swamp forest (Luly *et al.* 1980; Blackburn 1985; Kershaw *et al.* 1991). However, the predominantly lightening-upwards pattern identified from Markov chain analyses (Mackay *et al.* 1995) suggested the opposite. The presence of open water has also been questioned (Anderson and Mackay 1990). Sequence analysis suggests that the lithotypes may be more a reflection of climatic variation during sea-level highs than successional change in response to phases of subsidence (Sluiter *et al.* 1995).

In general terms, the taxa with well-dispersed pollen provide a regional picture of the vegetation, although many taxa will also have had a swamp forest representation. Coal formation began in the Mid Eocene after the Early Eocene global temperature peak. Temperatures continued to fall through the Eocene and this is reflected in the pollen by the increase in *Nothofagus* pollen. The decline in Podocarpaceae may be related to the general evolutionary replacement of gymnosperms by angiosperms. All taxa have strong rainforest affinities although there is some macrofossil evidence of the presence in Australia, and in the Latrobe Valley coals, of *Casuarina,* the sclerophyllous member of the Casuarinaceae, in the Miocene (Hill 1994), while components of the Myrtaceae, although not containing *Eucalyptus,* may also have been sclerophyllous. Within those taxa with poorly dispersed pollen, which must have derived from taxa growing within the swamp system, there is a general increase, particularly in the Morwell 1 and Yallourn seams. All are sclerophyll elements.

Throughout the whole recorded period the landscape was dominated by rainforest. However, the increase in light-demanding sclerophyll elements through time suggests that the vegetation was either becoming more open or was subject to increasing levels of disturbance or stress. The charcoal record is consistent with increased disturbance, being absent until the Early Miocene Morwell 1 seam and then increasing through to the Mid Miocene. These changes relate to increased lithotype differentiation in the coals which is likely to have been primarily due to increased climatic variability at Milankovitch or sub-Milankovitch scales (i.e. 100 ka or less). The data are too coarse to indicate any role of fire in the initiation of vegetation change but, from a fine-resolution study of a section of the Morwell 1 seam, Blackburn and Sluiter (1994) concluded that burning occurred after a change to drier conditions and development of a more sclerophyllous vegetation and was clearly a response to, rather than a cause of, vegetation change.

Although there are major differences between the vegetation and depositional environments of the Murray Basin and Latrobe Valley sequences, there are sufficient similarities between them within their period of overlap to suggest synchronous broad regional changes in fire activity. Charcoal values were low until probably the Late Oligocene, suggesting infrequent or low intensity burning under a climate with low-variability and limited sclerophyll development. Higher charcoal levels from the Late Oligocene to Early Miocene indicate more intense and widespread fire activity under more variable climates. There is increased representation of sclerophyll vegetation in both swamp and dry land environments. The major change to high charcoal levels, perhaps indicating fire activity almost as great as that in the Pleistocene, occurred within the Mid Miocene, by about 16 Ma BP, accompanied by a highly variable climate and, although precipitation is estimated to have been about twice that of today, the representation of sclerophyll vegetation was substantial.

Pleistocene fire activity

The focus of Quaternary palynological study has continued to be on the construction of records extending from the present as far back into the past as possible and, as a result of the high cost of drilling economically unimportant Quaternary sediments and the discontinuous nature of Quaternary sedimentary sequences, there is very little information on the vegetation or fire history of the Early Pleistocene. The record of Martin (1990) suggests that there was a substantial reduction in precipitation at the beginning of the Pleistocene with a major expansion of open woodland and forest vegetation. This pattern is supported by evidence from the more refined and better dated early record of Lake George to the east (Kershaw *et al.* 1994) which shows the virtual disappearance of rainforest taxa and expansion of more open vegetation around 2.5 million years ago. Unfortunately there are no charcoal data for either record but the nature of the vegetation and the fact that fire had become a significant feature of the environment suggests that burning would have continued through the Pleistocene period. The only pollen and charcoal record that extends into the Early Pleistocene is from a marine core (ODP Site 820) off the coast of north-east Queensland adjacent to the Atherton Tableland (Kershaw *et al.* 1993) (Fig. 1.1). This record indicates that burning was regionally important from around 1.4 Ma, despite the pollen suggesting that the landscape was dominated by wet rainforest and drier araucarian rainforest, with restricted representation of sclerophyll vegetation through most of the recorded period. The extended record from Lake George (Singh and Geissler 1985) which, from the location of the Brunhes/Matuyama palaeomagnetic reversal, can be firmly dated to the base of the Mid Pleistocene (*c.* 800 ka BP) continues to show that burning was a feature of the environment. However, charcoal–vegetation relationships above this boundary appear to be different from those in the later part of the Pleistocene. Their elucidation is made difficult by discontinuous representation of pollen.

There are now 10 records, including those from Lynch's Crater and Lake George, which cover at least the last glacial/interglacial cycle. Their locations, along with summary charcoal records, are shown in Fig. 1.1 for all except Old Lake Coomboo Depression on Fraser Island (Longmore and Heijnis 1999) whose chronology is most uncertain. Some information on the nine selected records is included in the longer list of site records in Table 1.1. The charcoal summaries are averaged values for time slices selected to represent major identified past climatic phases apart from the most recent two slices which represent early and late phases of European occupation. Time slices become shorter towards the present due to improved dating control and greater environmental understanding. However, it is only the more generalised Pleistocene record that will be considered in this section. Additional information on burning patterns is provided by the identification of major charcoal peaks in those records which are sufficiently refined to allow peak isolation (Fig. 1.4). Peaks during the Pleistocene are shown in relation to the SPECMAP marine oxygen isotope curve of Martinson *et al.* (1987) which provides a standard chronology for the late Quaternary. Positive $\delta^{18}O$ values relate to glacial periods when sea levels were low while negative $\delta^{18}O$ values indicate high sea-level, interglacial periods.

Almost all records show a general increase in charcoal abundance through time if climatic cycling at the Milankovitch scale is taken into account. In the Lynch's Crater, Banda Sea, Lake Wangoom and Egg Lagoon records, this increase is abrupt and takes place in the later part of isotope stage 3, centred on 30–40 ka BP. As has been noted, the charcoal increase at Lynch's Crater around 38 ka BP was accompanied by the beginning of the replacement of araucarian forest by eucalypt woodland and it has been hypothesised that increased burning was the cause of this sustained vegetation change. In the marine record of the Banda Sea, whose pollen is derived from both Indonesia and northern Australia, there is a marked reduction in eucalypts relative to grasses suggesting the development of a more open landscape. The impact of the increase in burning appears to have extended to Indonesia which experienced a marked and sustained reduction in Dipterocarpaceae, a canopy dominant of many Indonesian rainforest communities. Vegetation responses at the two other sites appear to have been minimal with some increase in grasses relative to daisies (Asteraceae) around Lake Wangoom within an open woodland landscape, and perhaps a sustained reduction in the extent of the rainforest and wet sclerophyll forest taxa *Phyllocladus* and *Pomaderris aspera* respectively with some epacrid heath development around Egg Lagoon.

The suggestion from Lake George that there was an earlier marked and sustained increase in burning with an associated alternation of the

Table 1.1. *Information about Quaternary pollen and charcoal sites shown in Figures 1.1 and 1.5*

Site Number	Site	Charcoal measure	Reference
1	Lombok Ridge	particles/cm^3	Wang *et al*. (1999)
2	Banda Sea	particles/cm^2 per yr + mg/cm^2 per yr	van der Kaars *et al*. (2000)
3	ODP Site 820	particles/cm^3	Moss (1999), Moss and Kershaw (2000)
4	Lynch's Crater	particles/cm^3	Kershaw (1986)
5	Lake George	surface area%/unit volume of sediment	Singh *et al*. (1981), Singh and Geissler (1985)
6	Lake Wangoom	particles/cm^3	Edney *et al*. (1990), Harle (1998)
7	Egg Lagoon	mm^2/cm^3	D'Costa (1997)
8	Lake Selina	not given	Colhoun *et al*. (1999)
9	Darwin Crater	not given	Colhoun and van de Geer (1988)
10	Burraga	cm.cm^2	Dodson *et al*. (1994c)
11	Boggy Swamp	particles/cm^2 per yr	Dodson *et al*. (1986)
12	Butcher's Swamp	particles/cm^2 per yr	Dodson *et al*. (1986)
13	Black Swamp	particles/cm^2 per yr	Dodson *et al*. (1986)
14	Sapphire Swamp	particles/cm^2 per yr	Dodson *et al*. (1986)
15	Penrith Lakes	particle size abundance scale	Chalson (1989)
16	Warrimoo	particle size abundance scale	Chalson (1989)
17	King's Tableland	particle size abundance scale	Chalson (1989)
18	Ingar Swamp	particle size abundance scale	Chalson (1989)
19	Notts Swamp	particle size abundance scale	Chalson (1989)
20	Katoomba Swamp	particle size abundance scale	Chalson (1989)
21	Burralow Creek Swamp	particle size abundance scale	Chalson (1989)
22	Killalea Lagoon	charcoal/pollen ratio	Dodson *et al*. (1993)
23	Bondi Lake	charcoal/pollen ratio	Dodson *et al*. (1993)
24	Bega Swamp	mm^2/ml	Green *et al*. (1988), G. Hope unpublished data
25	Rotten Swamp	cm^2/cm^2 per yr	R. L. Clark (1986)
26	Club Lake	cm^2/cm^2 per yr	Dodson *et al*. (1994a)
27	Tea Tree Swamp	charcoal/pollen ratio	Gell *et al*. (1993)
28	Lake Curlip	cm^2/cm^2 per yr	Boon and Dodson (1992)
29	Hidden Swamp	particles/cm^3	Hooley *et al*. (1980)
30	Loch Sport Swamp	particles/cm^3	Hooley *et al*. (1980)
31	Lake Wellington	mm^2/cm^3	Reid (1989)
32	McKenzie Road Bog	charcoal/pollen ratio	Robertson (1986)
33	Greens Bush	mm^2/cm^3	Jenkins and Kershaw (1997)
34	Cranbourne Botanic Gardens	particles/cm^3	Aitken and Kershaw (1993)

Table 1.1. (*cont.*)

Site Number	Site	Charcoal measure	Reference
35	Lake Mountain	charcoal/pollen ratio	McKenzie (1997)
36	Storm Creek	charcoal/pollen ratio	McKenzie (1997)
37	Tom Burns	charcoal/pollen ratio	McKenzie (1997)
38	Oaks Creek	charcoal/pollen ratio	McKenzie (1989)
39	Buxton	charcoal/pollen ratio	McKenzie (1989)
40	Powelltown	charcoal/pollen ratio	McKenzie (1989)
41	Lake Horden	particles/cm^3	Head and Stuart (1980)
42	Chapple Vale	charcoal/pollen ratio	McKenzie and Kershaw (1997)
43	Wyelangta	mm^2/cm^3	McKenzie and Kershaw (2000)
44	Aire Crossing	mm^2/cm^3	G. M. McKenzie unpublished data
45	West Basin	particles/cm^3	Gell *et al*. (1994)
46	Cobrico Swamp	mm^2/cm^3	Dodson *et al*. (1994b)
47	Lake Keilambete	cm^2/cm^3	Mooney (1997)
48	Northwest Crater, Tower Hill	particles/cm^3	D'Costa *et al*. (1989)
49	Main Lake, Tower Hill	particles/cm^3	D'Costa *et al*. (1989)
50	Lake Turangmoroke	charcoal/pollen ratio	Crowley and Kershaw (1994)
51	Jacka Lake	particles/cm^3	C. Greenwood unpublished data
52	Lake Tyrrell	mm^2/cm^3	Luly (1993)
53	Bridgewater Lake Core A	charcoal/pollen ratio	Head (1988)
54	Boomer Swamp	charcoal/pollen ratio	Head (1988)
55	Long Swamp	charcoal/pollen ratio	Head (1988)
56	Lashmar's Lagoon	particles/cm^3	Singh *et al*. (1981)
57	Lake Flannigan, King	mm^2/g	D'Costa (1997)
58	Killiecrankie, Flinders	charcoal/pollen ratio	Ladd *et al*. (1992)
59	Stockyard Swamp, Hunter	charcoal/pollen ratio	G. Hope unpublished data
60	Sundown Point, Hunter	charcoal/pollen ratio	G. Hope unpublished data
61	Lake Johnson	g	Anker (1991)
62	Poets Hill	charcoal/pollen ratio	Colhoun (1992)
63	Melaleuca Inlet	charcoal/pollen ratio	Thomas (1995)
64	Dublin Bog	charcoal/pollen ratio	Colhoun *et al*. (1991)
65	Den Plain 2	particles/cm^3	Moss (1994)
66	Ringarooma River	cm^2/cm^3	Dodson *et al*. (1998)
67	Big Heathy Swamp	charcoal/pollen ratio	Ellis and Thomas (1998)

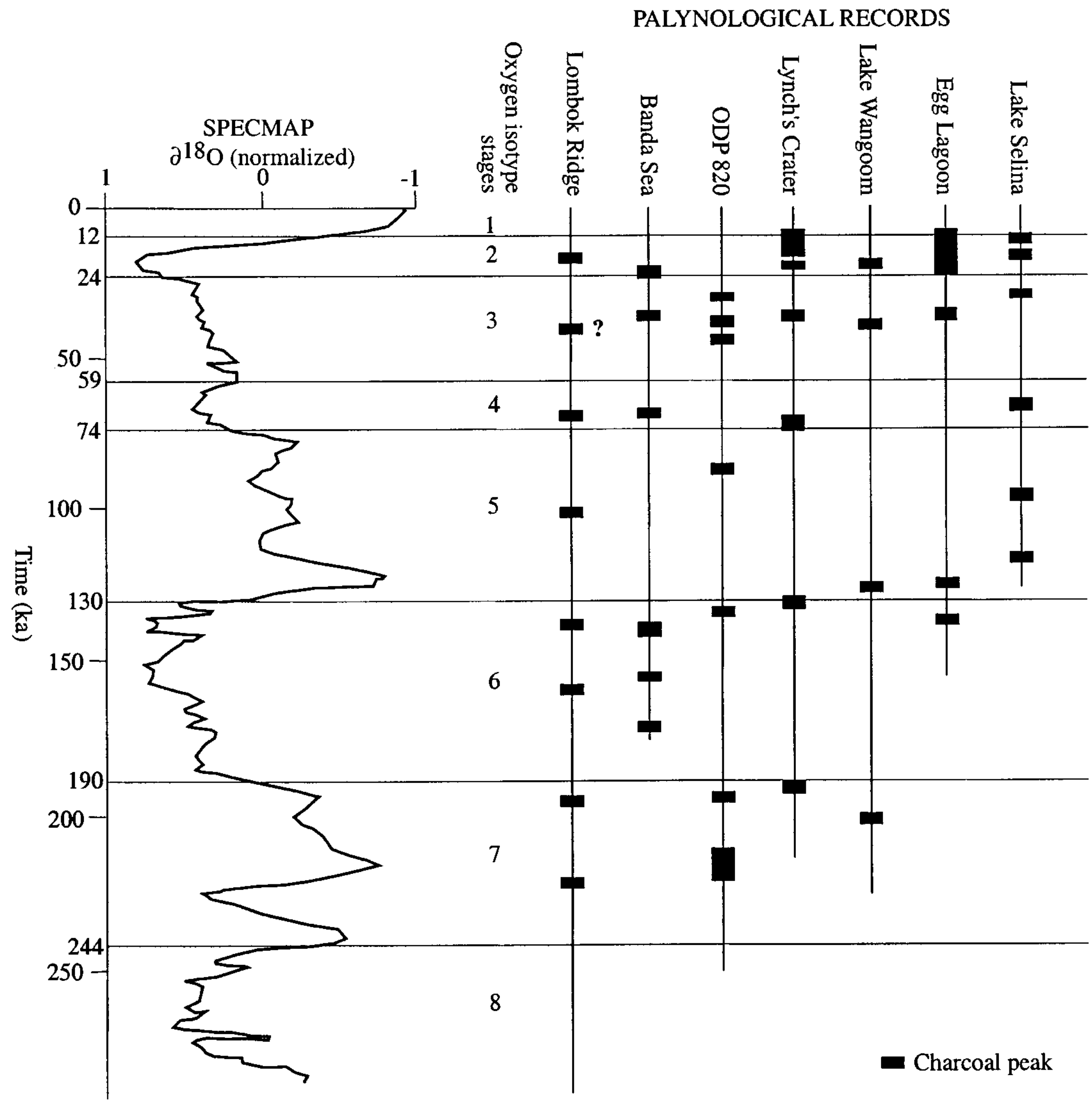

Fig. 1.4. Charcoal peaks in long continuous records from the Australian region in relation to the marine oxygen isotope (SPECMAP) record of Martinson *et al.* (1987).

vegetation receives some support from the ODP Site 820 where higher charcoal levels around 135 ka BP are closely associated with a sharp decline in *Araucaria* and some increase in the representation of *Eucalyptus*. Despite the proximity of Lynch's Crater to this site, there are no similar changes recorded at that time. However, the 38 ka BP event at Lynch's Crater appears to be recorded in the ODP site 820 record with a further decline in *Araucaria* and further increase in *Eucalyptus* in association with increased charcoal levels. There are also sustained changes in vegetation around 175 ka BP, with a change in dominance from *Eucalyptus* to Poaceae in the northwestern Australian pollen component of the Lombok Ridge marine core and increased values for Poaceae and declines in ferns and palms within the ODP site 820 record, but neither has an associated charcoal event.

Darwin Crater (Tasmania) is the only record where there is a general decrease in averaged charcoal values through the last three glacial cycles, although there appears to be a major and sustained increase in herbs relative to rainforest and open-forest trees within what is estimated to be isotope stage 6. Jackson (1999) suggests that these changes were the result of an increase in burning which resulted in an ecological drift to a more open landscape and that the reduction in charcoal abundance was due to lesser quantities being produced from herbaceous vegetation than rainforest or eucalypt forest. However, through the full estimated 500 ka of the record, there are few overall trends in either the vegetation or charcoal abundance.

The effects of climatic cyclicity on charcoal representation are evident in most records where cycles are not totally obscured by trends of increasing values. Charcoal levels are higher in glacials than interglacials at all northern Australian sites, although values are extremely low and sporadic at Lynch's Crater, and have been interpreted as indicating more frequent burning under drier conditions. In southern Australia this pattern appears to be evident at Lake Wangoom and, surprisingly, at Darwin Crater, where less charcoal might have been expected under the more open landscapes of the glacial periods in light of the Jackson hypothesis. At Lake George, which exists under drier conditions than any of the other sites, lower charcoal values within glacial phases have been explained as due to the inability of the sparse cover of vegetation to support regular fires.

Another perspective on burning patterns is provided by the plots of charcoal peaks on Fig. 1.4 which may indicate times of high fire activity. There are concentrations of dates within the maxima of the last glaciation (stages 4 and 2) and the penultimate glacial (late stage 6), which could be interpreted as providing general support for the proposal that these drier periods were times of generally higher fire activity. However, it could be argued that the majority of these events are close to isotope stage boundaries and relate more to times of rapid climate change than extreme climatic conditions. This interpretation receives support from a high proportion of the peaks which fall within interglacials. The major exception to this pattern is the presence of at least one charcoal peak within all records during the period 30–40 ka BP which, according to the marine isotope record, may have been one of the most climatically stable periods within the last 280 ka. Other charcoal peaks may relate to times of substantial climate change within isotope stages.

A somewhat different picture to that provided by Singh *et al.* (1981) on the pattern of burning and its impact on Australian vegetation is provided by this more substantial, though still geographically biased, data set. Limited data for the early part of the Quaternary indicate that fire has been a major component of the environment throughout this period and that, although there has been an increase in fire activity through at least the last glacial cycle with perhaps stepwise changes around the proposed dates of 130 and 40 ka BP, late Quaternary vegetation changes have been less dramatic than originally suggested. These data require a re-evaluation of the relative roles of climate and Aboriginal people in the production of fire and vegetation changes.

It is always difficult to separate totally the effects of climate and people on the fossil record as climate will have some influence on human activity. This influence is considered to be nowhere more apparent than in Australia where initial colonisation and possible impact is likely to have been related to climate-induced changes in sea-level and opportunities for short sea-crossings through the Indonesian Archipelago. In addition, any substantial human impact on the vegetation cover could lead to climate change as is evident with current greenhouse forcing. However, it seems unlikely that human impact could have been a significant factor in those trends and abrupt changes witnessed in the Lombok Ridge and ODP site 820 records that are evident as far back as 170 ka BP, well beyond the limit of the archaeological record. Furthermore, there is either no great correspondence between vegetation alterations and charcoal peaks or the initiation of vegetation change appears to have preceded charcoal peaks in earlier events, suggesting that fire may have been more a result than a cause of vegetation change. At Lake George, it was argued that the presence of people could not be detected until the beginning of the penultimate interglacial, some 130 ka BP, when the vegetation cover became sufficiently complete to carry fire. This argument cannot be extended to records from other sites situated within wetter environments. The general pattern of charcoal representation and/or inferred burning levels is that there has been strong climatic control over fire patterns with greater activity during drier glacials than interglacials (although the opposite may have been the case in environments similar to and drier than those around Lake George), with maximum burning during periods of substantial climate change.

The major exception to this pattern, at least in the Pleistocene, was during stage 3 when there were major sustained changes in the vegetation, particularly in northeastern and northern Australia and charcoal peaks in almost all other records at a time of relative climatic stability. The degree of synchroneity of these events is uncertain due to problems of dating so close to the limit of radiocarbon but they fall, almost certainly, within the period 45 to 30 ka BP. As people are known to have occupied most of the continent by this time, and as there is a close association between evidence for increased burning and vegetation change within the records, it might be fairly concluded that Aboriginal burning was the major causal factor and could well have impacted the whole of the Australian landscape, as well as some parts of Indonesia, within a short period of time.

The timing of presumed human impact is interesting in light of the archaeological debate over the actual timing of the arrival of people. Assuming that the colonisation process was rapid and impact was immediate, the data add support to the school of thought that accepts the validity of radiocarbon dates and that people arrived around 40 ka BP (Allen and Holdaway 1995) rather than the increasing number of sites dated by other methods including thermoluminescence (Roberts *et al.* 1990), optically stimulated luminescence (Roberts *et al.* 1993) and electron-spin resonance and uranium/thorium (Thorne *et al.* 1999) for a 50 to at least 60 ka BP arrival date. In fact there is a marked absence of charcoal peaks between 50 and 60 ka BP.

The data suggest that there has been a close relationship between climate and fire through the late Quaternary period although global climate, as reflected in the SPECMAP isotope curve, does not indicate any clear climatic trend through the last 280 ka. From about 40 ka BP, the directional change towards increased burning and more open vegetation can be attributed to an additional anthropogenic source of ignition but this appears to have resulted in an acceleration of an existing trend rather than the initiation of it. One climatic explanation for the trend is that the effectiveness of fire increased with a change to higher-amplitude glacial oscillations, which produced a great deal of vegetation instability within the 1Ma to 700 ka (Shackleton *et al.* 1995). The effects of individual fires may have been cumulative through the process of ecological drift proposed by Jackson (1968). In his model, burning results in the repeated expansion of one community at the expense of another, in sequence, according to a shift in mean fire interval. If fires are sufficiently frequent or intense, then the vegetation change can be permanent. The process can be facilitated by the negative long-term effects of burning on the physical and chemical properties of soil, with alterations to soil moisture-holding capacity and fertility helping to maintain more open, sclerophyllous and hence more flammable vegetation. However, such a trend might be expected to have been global, which does not seem to have been the case. It is possible, however, that Australia has experienced a different late Quaternary climate history to much of the rest of the world. Isern *et al.* (1996) and Peerdeman *et al.* (1993) detected a change in oxygen isotope values of marine cores in the Coral Sea region some 500 to 250 ka BP which were interpreted as an average increase of about 4 °C in sea surface temperatures. Such an increase may be expected to have increased precipitation in northeastern Australia, due to increased evaporative power of the ocean, and perhaps cause a decrease rather than an increase in fire activity. However, if, as Isern *et al.* (1996) suggest, this temperature increase was related to the development of the West Pacific Warm Pool, then the production of a steep temperature gradient across the Pacific Ocean may have satisfied the prerequisites for the establishment of El Niño–Southern Oscillation (ENSO) variability, a major feature of Australia's climate. Even with higher precipitation, increased occurrence of droughts would have most likely allowed increased fire activity within the Australian landscape.

Holocene fire activity

A substantial number of palynological records with associated charcoal curves cover part or the whole of the Holocene period (i.e. the last 10 ka). The variability of charcoal representation within these records has led to the postulation of a whole range of suggestions about the relationship between fire, climate, various components of the vegetation and people. In order to determine and attempt to explain any consistent patterns of fire activity, a regional approach to data analysis has been adopted. Attention is focussed on southeastern Australia as this is where the majority of studies have been undertaken (Fig. 1.5).

From all available records, 58 were considered to have the resolution and dating control required for analysis of patterns in relation to the younger time slices identified in the longer records in the previous section. The location of these records, which in fact exclude the longer records from this region, are shown on Fig. 1.5 while some information about them is contained in Table 1.1. The 11–9 ka BP time slice represents the transition between the Pleistocene and the Holocene and covers a period of vegetation change in relation to increasing precipitation. The period 7–5 ka BP is identified as the Holocene precipitation peak, the time slice 4–2 ka BP incorporates a drier and perhaps cooler phase before a return to wetter conditions in the last 2 ka. The European time slices are identified on evidence for disturbance to the native vegetation and on weed pollen indicators. Chronological control is generally poor within the European period and although 1940, when fire-exclusion policies were introduced, was adopted as the nominal date for separation of older and younger European phases, only estimates of this date could be made for most records.

Because of differences in charcoal counting and presentation methods, and the variation in charcoal abundance related to the nature and size of the depositional basins from which the records were derived, it was considered that charcoal abundance measures could not be used to determine temporal and spatial patterns of fire activity. Instead, a simple ranking was undertaken initially of relative charcoal values in each time slice for each record. For example if a record covered all time slices the rankings would range from 6 for the time slice with the highest charcoal value to 1 with the lowest charcoal value, and if only the last three time slices were recorded (the minimum number in the data set) the rankings would range from 3 to 1. The average of the ranking values for time slices from all sites, and for subsets of sites surrounded by present-day wet forest (rainforest and tall open-forest), dry (open) forest, heath and woodland, were calculated and are shown on Fig. 1.6. Some sites were not included in the subsets either because the original vegetation cover was uncertain or the vegetation did not clearly fit into these groups. Conversely, a few sites which were surrounded by a mix of two community types were included in both relevant subsets. In addition to these summaries, times of identified charcoal peaks within any of the records from the data set, which may represent major fires or discrete times of intensive fire activity, are shown on Fig. 1.7.

The overall impression is that fire activity has been relatively constant over the Holocene period with greatest variation during the period of European occupation. The data suggest that burning increased during the early part of European settlement to levels higher than at any other time during the Holocene in all major vegetation types, a conclusion that was also reached by Singh *et al.* (1981). The increase was least within wet forest which may be due to contained areas being remote from major areas of land clearance and utilisation. This period was followed by a reduction in burning to present-day levels which are, on average, lower than at any time during the Holocene. However, levels in dry forest and heath environments appear still to be higher than those in the Early to Mid Holocene. The timings of the onset of high fire activity and the sub-

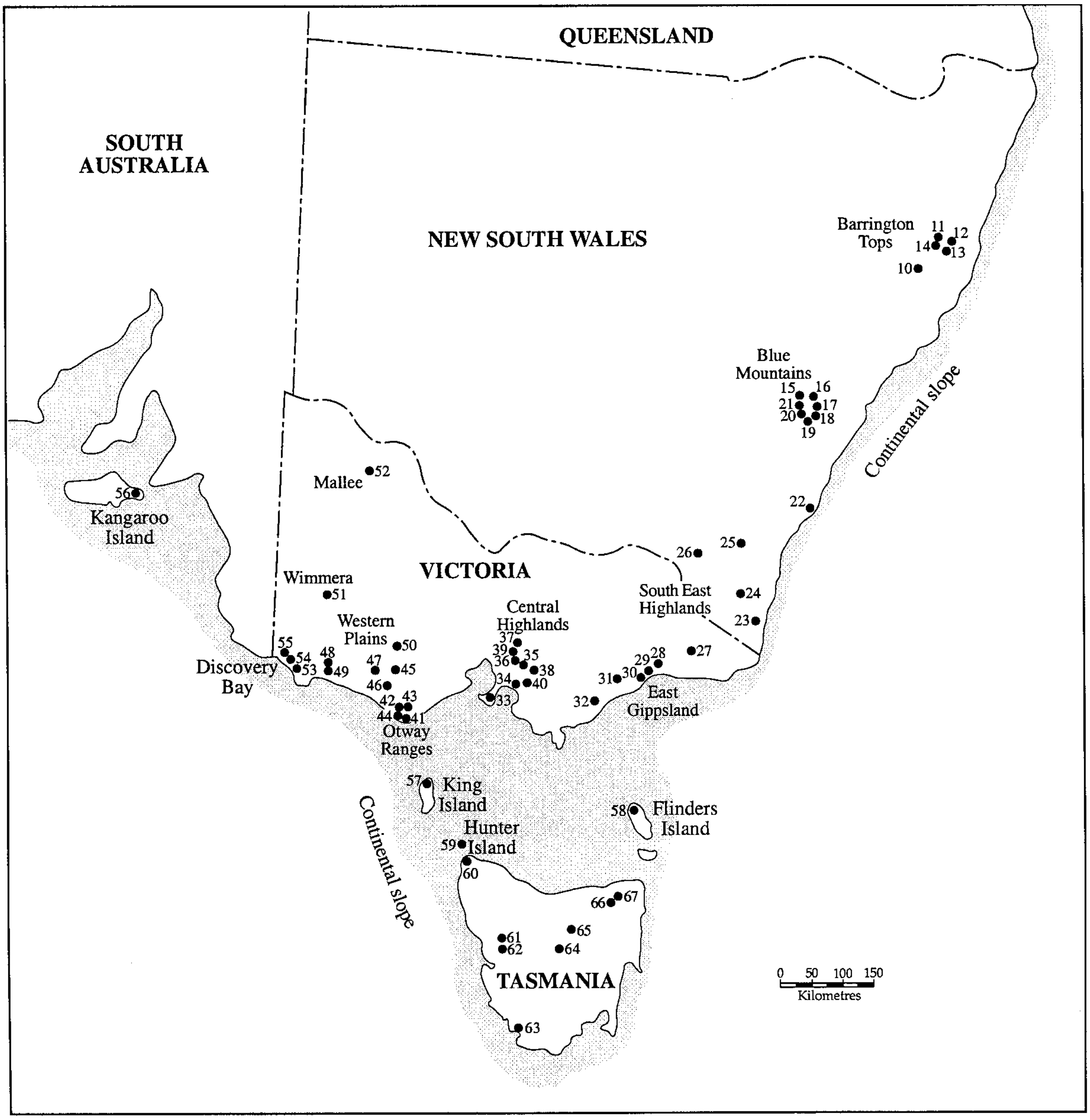

Fig. 1.5. Location of late Quaternary pollen and charcoal sites from south-eastern Australia examined in this chapter.

sequent transition from high to low levels of burning in the European occupation period are difficult to pin down due to a lack of absolute dating for most sites. Radiocarbon dates tend to be inaccurate or lack appropriate precision for these recent periods leaving ^{210}Pb dating as the only radiometric method which can be used, in addition to less certain markers associated with historical events. Even with ^{210}Pb, accurate dating can only be achieved for the last 100 years and for certain records. It appears that the time of onset as well as the duration of high burning levels varied from place to place. Such variation is illustrated by fine resolution studies from McKenzie Road Bog, South Gippsland

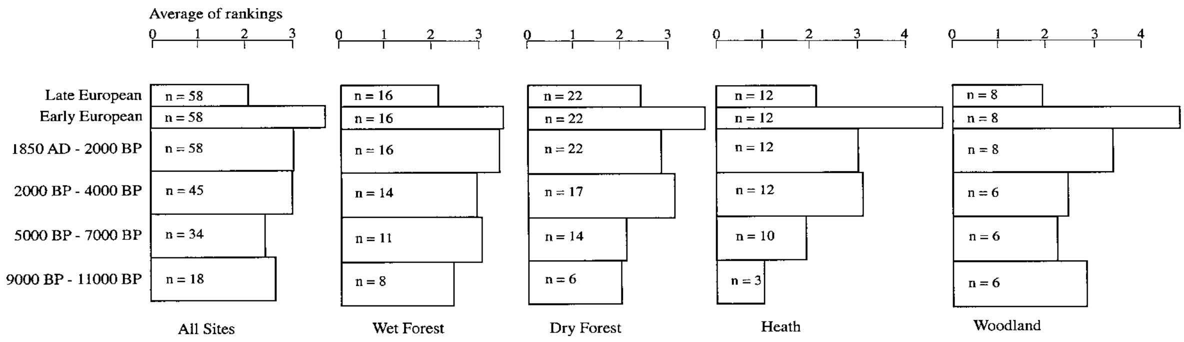

Fig. 1.6. Relative importance of burning in time slices from the Holocene deduced from individual site rankings of charcoal abundance for all site records, and separately for wet forest, dry forest, heath and woodland site records, in south-eastern Australia.

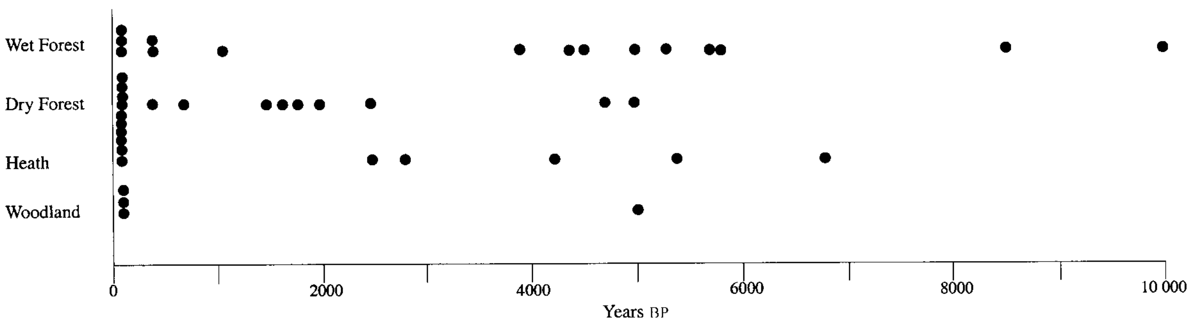

Fig. 1.7. Charcoal peaks recorded in the site records from south-eastern Australia shown in Fig. 1.5.

and Delegate River, East Gippsland. At McKenzie Road Bog, dated by detailed comparison with the historic record, the high burning phase occurred from about 1850 to 1890 (Robertson 1986) while at Delegate River, ^{210}Pb dating indicates that high fire activity did not cease until suppression measures were implemented after the socially disastrous 1939 fires (Gell *et al.* 1993). In some fine-resolution records (e.g. Dodson *et al.* 1998 from rainforest in Tasmania; C. Greenwood personal communication in the Victorian Wimmera) there is no evidence of an increase in burning since European arrival. The coarser-sampled records of the Barrington Tops region also show no increase in fire activity with the arrival of Europeans although, without absolute dating control, fire peaks considered to have occurred about 400 years ago might possibly represent early European burning.

The influence on the vegetation of alterations to fire activity resulting from European activities is difficult to gauge as the bulk of changes within pollen records can be attributed to local or regional clearing which may or may not have involved fire. In coastal and western Victoria there was a general decrease in Casuarinaceae relative to *Eucalyptus* which has been interpreted as a result of European burning but no firm relationship can be detected within fine-resolution records. It is most likely that the casuarinas were selectively removed for firewood and other purposes. It has been suggested that disruption to the Aboriginal fire regime resulted in an increase in understorey shrubs relative to grasses within open-forest. However, the East Gippsland study of Gell *et al.* (1993) suggests exactly the opposite with an increase in grasses during the early European high burning phase and a decrease to present with the implementation of fire-control measures.

Within the pre-European part of the Holocene, there is a general increase in burning through time although there may have been a slight reduction in the Mid Holocene, between 7 and 5 ka BP, in response to an increase in rainfall and reduction in seasonality (Kershaw 1998). There was a significant increase in burning after 5 ka BP in all vegetation types, except the wet forests, and high fire activity was generally maintained or further increased after 2 ka BP. Increased burning is also suggested by the presence of charcoal peaks which centre on 5–4.5 ka and on 2 ka BP. The increase in burning may well have been a result of decreased precipitation after about 5 ka BP and high burning levels sustained by an onset or increase in activity of ENSO postulated for the region from this time (McGlone *et al.* 1992). A relationship with people may also be inferred from evidence of 'intensification' of occupation between 5 and 4 ka BP (Lourandos 1985). Although this concept has been hotly debated (see Head 1989; Dodson *et al.* 1992), a recent systematic study of the evidence for human occupation provides full support for both intensification and a high degree of synchroneity throughout Australia (Lourandos and David 2001). The relative importance of climate and human influence is difficult to assess but evidence of increased burning around this time from sites in New Zealand, where there is no suggestion of the presence of people, but where ENSO has a significant influence (McGlone *et al.* 1992; Ogden *et al.* 1998), suggests that climate was the major driving force.

The major burning response in the Mid Holocene was in heath and also open-forests which frequently contain a heath understorey. In general terms, this increase and the evidence for fire peaks around 5 and 2 ka BP provide regional support for the original Holocene fire record of R. L. Clark (1983) from such vegetation on Kangaroo Island in Singh *et al.* (1981). However, there is little support for the postulation of fire, as a result of Aboriginal burning, creating a replacement of Casuarinaceae woodlands by heath and eucalypt vegetation. Although *Casuarina* woodlands regionally declined, they did so at different times and generally without an obvious burning cause (Ladd 1988). In the Western Plains of Victoria, their decline may have related to an increase in precipitation around 7 ka BP, while on coastal areas leaching of dune soils is likely to have favoured replacement by eucalypt and heath vegetation (Ladd *et al.* 1992). The development of eucalypt and heath vegetation would have favoured fire activity though, and this may help explain the more substantial increase in burning through the Holocene in these environments. The suggestion of R.L. Clark (1983) that a further increase in charcoal about 2.5 ka BP was the result of a change from regular low-intensity fires to less frequent high-intensity fires with the abandonment of Kangaroo Island by people is not supported by evidence from similarly 'abandoned' islands such as Flinders, King and Hunter. Burning did continue but at similar levels to those occurring previously.

General discussion and conclusions

The three scales of analysis of the pattern of burning on the Australian landscape, although limited in geographical spread and data type and consistency, have provided some quantitative basis for assessment of the history of fire in relation to environmental and vegetation change.

There is a general impression of an increase in fire activity through the late Cainozoic in association with drier and more climatically variable conditions and an increasingly fire 'tolerant' vegetation. The data, however, are insufficient to allow a determination of the degree to which fire has promoted the development and expansion of more open vegetation. Through most of the recorded period climate appears to have been the driving force of vegetation change with fire largely responding to vegetation changes. Although only crudely quantified, the Murray catchment records suggest that high levels of burning, in association with a wet sclerophyll forest, were achieved several million years ago, before the onset of the dramatic fluctuations in climate which have characterised the Quaternary and particularly the late Quaternary. The continuing drying trend has inhibited the preservation of a Quaternary palaeoecological record in this area, but it might be inferred that fire activity has been reduced with the establishment of a more open vegetation.

There were marked vegetation changes in mainland southeastern Australia around the Tertiary–Quaternary boundary with a substantial reduction in the extent of rainforest (Kershaw *et al.* 1994) but, despite the Murray catchment evidence for vegetation to attain and sustain high levels of fire activity, small patches of rainforest survived and managed to expand during brief, high-rainfall interglacial periods within the late Quaternary (D'Costa and Kershaw 1995; Harle *et al.* 1999). Even in Tasmania where it has been postulated that ecological drift, through vegetation feedbacks on fire and soil fertility, would have led to a progressive replacement of rainforest by more open vegetation (Jackson 1968), the net result on the vegetation around Darwin Crater over the last 500 ka has been a maintenance of the *status quo*.

In the humid tropics region of northeastern Australia there is little directional change in charcoal abundance or vegetation through much of the Quaternary period. There is a general increase in charcoal and a gradual replacement of the previously important araucarian forest by open sclerophyll forest and woodland during the later part of this period but the association between charcoal and vegetation change is not strong enough to demonstrate that fire was responsible for the initiation of this trend. It is likely that changes were climatically induced with droughts resulting from an increase in ENSO activity, superimposed on higher-amplitude Late Quaternary climatic cyclicity, being the critical features (Moss and Kershaw 2000). The evidence for some periodicity in ENSO activity from the Holocene records might help explain the stepwise decline of the araucarian forest.

The data suggest that the influence of human-induced burning on the development of the present vegetation cover might be much less than proposed by Singh *et al.* (1981) despite the fact that suggested times and patterns of charcoal increases have been recorded in additional records. The proposal of a human presence around Lake George by about 125 ka BP is not outlandish in light of sustained vegetation changes in other records at or before this time, but, as mentioned, the recent evidence for altered climatic conditions in this part of the world provides, for the first time, an alternative explanatory mechanism. In addition, the earliest archaeological evidence for the arrival of people, although still debated in detail, has firmed for most of the continent at between 40 and 60 ka BP. On the other hand, evidence for some human impact, centred on about 40 ka BP has been strengthened by both archaeological and palaeoecological data. At this time there was no major global climate change and, unless the suggestion of Moss and Kershaw (1999) that there may have been a major phase of ENSO variability can be confirmed, a climatic cause, or predominantly climatic cause, can probably be discounted. In both the Lynch's Crater and ODP Site 820 records, the evidence indicates a response of vegetation to burning rather than a vegetation change resulting in higher fire activity. However, the ODP site 820 record demonstrates that the change represents an acceleration in an existing process rather than a singular event, while the degree of vegetation change proposed in other records for which there is a burning signal is much less than that in the climatically sensitive humid tropics region.

By Holocene time, people had been present for at least 30 ka and it might be expected that some balance had been achieved with the landscape. The data suggest that this was the case, with major vegetation changes and burning activity consistent with the inferred pattern of climate change. The relatively fire 'sensitive' species *Allocasuarina verticillata (syn. Casuarina stricta)* had survived to dominate the vegetation of much of coastal and inland Victoria during the Early Holocene and was then replaced by eucalypts and heath in the later Holocene most likely due to increased moisture levels and leached soils (or even salinity: Crowley 1994a, b) rather than fire as previously suggested by Singh *et al.* and others. There is also little support for alteration of fire regimes with the disappearance of people from continental islands during the Holocene. Fire activity has been higher in the later Holocene and, although it corresponds to an intensification of human occupation, is more parsimoniously explained by vegetation changes associated with drier and particularly more variable climatic conditions.

The presumed extinction of a species of Casuarinaceae in the Holocene of the Lake George record that dominated several interglacial periods prior to the penultimate interglacial was considered central to the argument for continued impact of human burning on the landscape. However, Crowley (1994a) suggested that increasing salinity levels may have resulted in the decline of Casuarinaceae and the there is always danger in assuming a similar vegetation response to different interglacial periods. Whitlock and Bartlein (1997) demonstrated the marked impact that different patterns of orbital solar forcing could have on vegetation from one interglacial to another and might explain the very different representation of Casuarinaceae, probably *Allocasuarina verticillata*, in the last three interglacials (Harle *et al.* 1999).

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