FIRE REGIMES AND MANAGEMENT IN SOUTHEASTERN AUSTRALIA

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ABSTRACT

It is widely recognized that wildfires are a typical part of many Australian environments. They are caused by a combination of flammable vegetation, dry weather conditions, and both human and physical sources of ignition. Fires in most environments are of high intensity from time to time. Several land management authorities in the Sydney and Wollongong areas of southeastern Australia have responsibility for large tracts of native vegetation closely adjacent to major population centers. Although the primary management objectives of these "landowners" differ, in all cases prevention of serious wildfires is perceived to be a major responsibility and maintenance of the biota is viewed as an important objective. We argue that, in southeast Australia, little is known about the ecological effects either of large scale wildfires or of the management techniques commonly used to protect against them. A deliberate burning program that is successful in reducing the hazard of wildfire may compromise the primary management objective. Two main areas need greater research attention: (1) testing of the predictions of long-term community change from models generated from short-term studies of population dynamics and (2) incorporation of the extent and/or patchiness of a fire as an experimental factor. It is argued that research cannot be conducted effectively without the establishment of cooperative, long-term studies involving both land managers and research organizations, and this cooperation will facilitate the feedback of research findings into management policy.

INTRODUCTION

It is widely recognized that Australia contains many fire-prone regions (Mount 1970, Gill et al. 1981). Almost every year there are news reports of a wildfire burning out-of-control somewhere on the continent. These fires threaten human life and property and this creates the necessity for wildfire control. The history of the development of mechanisms of fire control is a familiar one (Gill 1981, c.f. Pyne 1982 for this history in the US). Years of complete suppression were followed by large conflagrations in forests with high fuel loads, and this stimulated the adoption of various forms of fuel reduction, usually by deliberate fires applied frequently and at a time of year in which they could be controlled.

We consider that there is a widely held understanding among the Australian public, in contrast to the attitude in the United States revealed by the 1988 Yellowstone wildfires, that the native vegetation has the capacity to recover from the large scale wildfires which can cause so much damage to human life and property. It has therefore been relatively easy to justify the imposition of frequent, regular, hazard-reduction fires as having great practical advantages while also being ecologically sound (Richmond 1981). Good (1981), for example, stated: "To date most planned fires have been implemented on the grounds of hazard reduction, with the maintenance of species diversity and fire dependence being post-fire justification for its implementation."

Various organizations and community groups have strongly-held opinions about the ecological effects of both wildfires and hazard-reduction burning ranging from "all fire is bad, complete suppression is needed" to "burn it all frequently in hazard-reduction fires and all wildfires can be prevented." Supporting the first philosophy is the observation that most fires are seen to kill or otherwise remove individuals of various plant and animal populations; supporting the second is the observation that individual organisms of some species can be seen to survive a fire and populations of some species appear to recover readily after a given fire—indeed some species appear to do better if burned than if left unburned.

Fire policies in Australian national parks are currently under the same sort of scrutiny from the press, the public, and politicians as has been experienced in the United States post-Yellowstone (e.g. *The bush can be made safer*, Sydney Morning Herald, 16 March 1983). This scrutiny is placing increasing pressure on the owners and custodians of large tracts of land to prevent future conflagrations, and especially to prevent them from burning into neighboring property. A consequence of this is a great deal of emphasis placed on "protecting one's neighbors," to the extent that this consideration has the potential to conflict with other management objectives.

In light of this background what are the research needs of land managers in relation to high-intensity fires in large areas of natural vegetation in eastern Australia? We argue here that knowledge of long-term ecological consequences of fire are necessary in order to defend any fire management policy, and there is currently very little information available (Clark 1988). We need to know more about the relative ecological consequences of high-intensity wildfires and the alterative fire regimes that are imposed to prevent wildfires. This means focussing on the responses of the biota to experimentally manipulated fire intensities, fire areas, fire frequencies, and fire seasons.

In order to explore the research needs in relation to management of high-intensity fire, in this paper we present the following:

(1) A background of the fire situation in the Sydney and Wollongong region of southeastern Australia, because there are important similarities and differences with various North American systems;
(2) A review of some of the evidence suggestive of ecological problems associated with the currently-favored, hazard-reduction fire regime;

(3) A review of some recent developments in the integration of research in plant population responses to fire and fire management in New South Wales, especially pertaining to national parks;
(4) Some warnings against blind adoption of preliminary research findings as a basis for projections of community change under a given management plan.

THE SYDNEY-WOLLONGONG AREA

Sydney and Wollongong are large urban areas bounded on three sides by large tracts of protected, relatively undisturbed ecosystems. These include large national parks to the north, west, and south of Sydney. To the west of Wollongong there are large areas of water board catchment and there are large national parks to the north (Royal National Park, which was established just a year after Yellowstone) and to the south (Morton and Budderoo national parks).

Important features of this geography are the juxtaposition of large urban areas and tracts of protected land and also enclosures of relatively small residential developments deep within bushland areas. These features produce two problems of relevance to the theme of this volume: (1) there is no shortage of ignition sources and (2) there is the potential, regularly realized, for substantial loss of life and/or property.

The vegetation in this area is heterogeneous, with sandstone soils supporting a mixture of forest, woodland, and sedgelands (heaths) (Fig. 1). The sandstone is deeply dissected by large gorges, so there are topographic discontinuities (Fig. 2) and certain aspects combined with areas of richer soil permit the persistence of patches of wet eucalypt forest and rainforest (Fig. 3). Most of these plant communities, with the exception of rainforest, are flammable under the appropriate climatic conditions. Historically, fire regimes occurring in these communities would have differed markedly, with eucalypt woodlands and sedgelands supporting relatively frequent fires, mostly of low to moderate intensity, and tall open forests receiving fires rarely, but those which did occur would have been of high intensity. Fires would rarely penetrated rainforest areas, with fires in adjacent eucalypt forest dying out as they burned into the rainforest margin (see Gill et al. 1981).

The large areas of forest, woodland, and heath adjacent to Sydney and Wollongong are controlled by various management authorities (The National Parks and Wildlife Service, Water Board, mining companies, etc.) with a variety of different primary objectives. The National Parks and Wildlife Service of New South Wales (NPWS) considers "preservation of species" or "preservation of communities" as being of primary importance (Barratt 1983), and other authorities (e.g. Sydney Water Board) see these objectives as both important and achievable.

Figure 1. Example of the eucalypt woodland and sedgeland communities occurring on the sandstone plateau in the Sydney-Wollongong region. A large proportion of this flora is tolerant of fire, resprouting from lignotubers or epicormic meristems. (Photograph by G. Taylor)

The Current Fire Regime

As mentioned above, the proximity of large urban areas to tracts of native vegetation provide ample opportunities for ignitions. Thus fires in the area can occur frequently. Most fires are started by humans and most are detected and controlled readily (Weir 1988). However, from time to time, the climatic conditions provide the opportunity for the development of serious wildfires should ignition occur. Recent examples of such occurrences were 1983 (Morton National Park) and 1988 (Royal National Park).

In an attempt to protect against the serious wildfires, hazard-reduction burning is frequently applied to large areas of national park, water catchment, and other areas. Depending upon the effectiveness of the program, fire frequency of this regime may vary from every five years to about every decade (Petrie 1983). The forest services in Australia were largely responsible for the refinement of hazard-reduction burning as a management technique and simplified instructions for implementing it are readily available to wildlife managers and fire control personnel. The technique was designed primarily to protect commercially valuable timber resources from damage caused by wildfire with little consideration of the effects on those components of the forest ecosystem which have no commercial value.

Figure 2. Topographic discontinuities such as cliffs (a) and, on a smaller scale, sandstone outcrops (b) break up fuel and cause patchiness in fire behavior. (Photograph by G. Taylor)

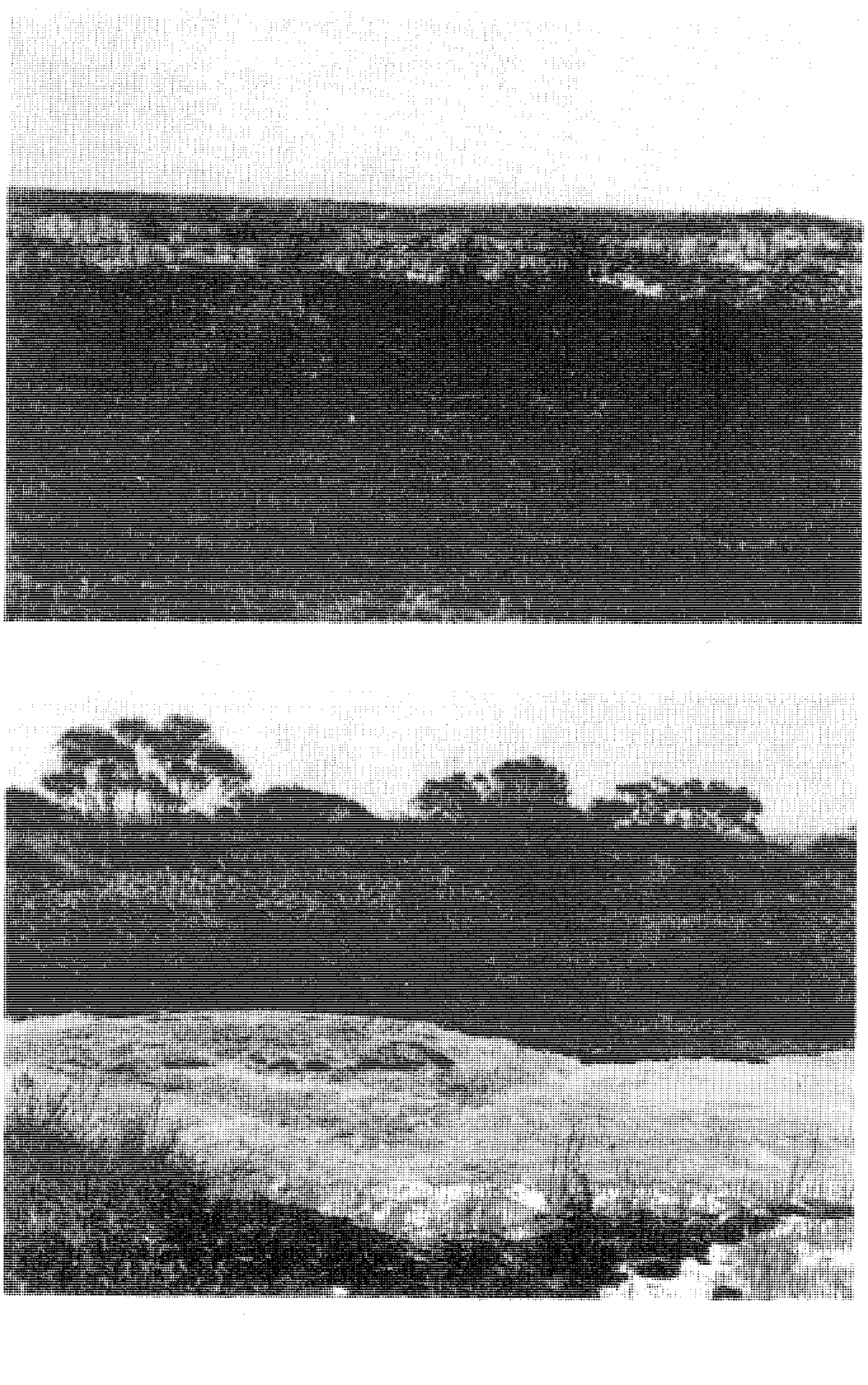


Figure 3. Tall open (eucalypt) forest and patches of rainforest occur on better soils in locations protected from desiccating winds and frequent burning. In the past, tall open forests have been burned infrequently, in high intensity fires. Rainforests have rarely burned throughout, fires usually going out as they reach the margin of a rainforest patch. (Photograph by G. Taylor)

Areas of national park and water catchment in Australia are managed for objectives other than commercial timber production. However, the popular perception of the vegetation in these areas as fuel for wildfires has prompted the application of forestry fire management techniques by people who lack the appropriate ecological information about the system they are manipulating. It is surely likely that the manipulated fire regime, designed for the protection of a small number of forest tree species, may cause changes in a great number of plant and animal communities whose responses to various fire regimes are unknown.

It is generally accepted that the combination of frequent arson ignitions and hazard-reduction burning in the Sydney area produce a fire regime that differs from the historical regime. In particular, fires are considered to be more frequent, generally of lower intensity, of smaller area, and in a different season of the year. However, it is difficult to know just what the historical regime was. Reconstructions of fire histories are not very good, even for post-settlement times; there are limitations to inferences based on anthropological evidence of Aboriginal burning and to the interpretation of pollen/charcoal data. Using these techniques we may be able to get some idea of area and frequency but not of intensity, season, or fine scale heterogeneity.

Ecologists and managers have argued that long-term ecological problems should be expected with the imposition of an "unnatural" fire regime simply because elements of the biota have evolved under one set of fire conditions and are now exposed to a different set. This may be a reasonable argument, but there are several problems which managers must deal with. First, historic fire regimes cannot now be mimicked perfectly for at least two reasons: (1) increased dissection of formerly continuous tracts of vegetation by urban and agricultural land, roads, rail line, and other firebreaks limit the spread of most fires and (2) increased frequency of ignition sources (e.g. arsonists) regardless of season. Second, permitting or imposing large-area and/or high-intensity fires in a hot, dry season challenges the technology of fire control and will meet with public and political opposition. For example, it would universally be considered unacceptable to conduct a high-intensity, management fire in conditions of high fire danger, whatever the ecological benefits may be. Compromises may therefore have to be found which achieve the desired ecological effects without putting neighbors' properties at increased risk.

In the context of these compromises, the "limits of tolerance" of the flora or fauna to changing fire regime may be more important than uncovering the precise historic fire regime. Kilgore (1983) stated that, in our attempts to mimic "natural fire" we should distinguish between (1) imposing burns within the range of intensity, frequency, season, and size found before the arrival of technological Europeans and (2) yielding the range of fire effects found prior to European arrival.

In this paper, we present and explore two related propositions. (1) Results of experimental studies of the ecological effects of a variety of fire regimes, at the population and community levels, are badly needed if anyone is to be convinced of the need for imposing any particular fire regime. (2) We don't have very much of this sort of information. Instead we have a set of incomplete "cautionary tales" about the potential damage that might result from a fire regime incorporating fires that are too frequent, too small, or too cool.

Imposing a Fire Regime—Potential Problems

Too frequent: the fate of "obligate seeder" shrubs

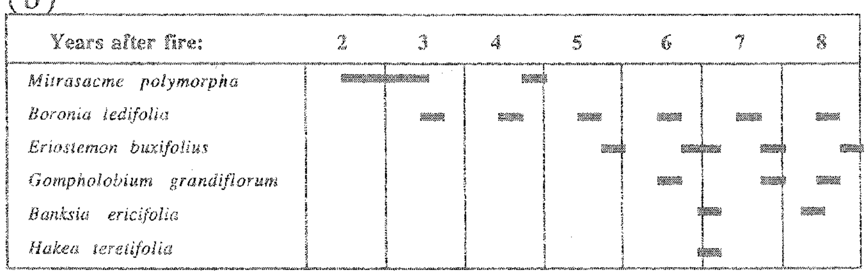
Banksia ericifolia is the classic eastern Australian cautionary tale, much quoted (e.g. Bradstock and Myerscough 1981, Zammit and Westoby 1987, Weir 1988) as an example of a plant species unable to tolerate frequent fires. This is one of a group of species defined as obligate seeders—species responding to fires by germination from a seed bank (stored in the canopy, for this species) even though established plants die when burned. Like many woody, perennial plants this species takes several years, up to 7 or 8, to reach first reproduction (Benson 1985) (Fig. 4). Consequently, a second fire in a *B. ericifolia* population occurring before a sufficient seed bank had developed would cause

Figure 4. Time to first flowering for shrub species in Hawkesbury Sandstone plant communities near Sydney shows substantial variability both among sites (a) and among species (b) (Data from Benson 1985).

(a)

	Years to first flowering in SITE:-				
	A	B	C	D	E
Actinotus minor	2	-	-	3	-
Gonocarpus teucroides	2	-	4	-	-
Boronia ledifolia	4	-	-	5	-
Gompholobium grandiflorum	4	-	-	6	-
Eriostemon buxifolius	-	-	5	5	4
Acacia suaveolens	-	-	-	5	4
Hakea teretifolia	6	6	-	7	-
Petrophile pulchella	-	6	-	9	8
Banksia ericifolia	8	8	-	7	-

(b)



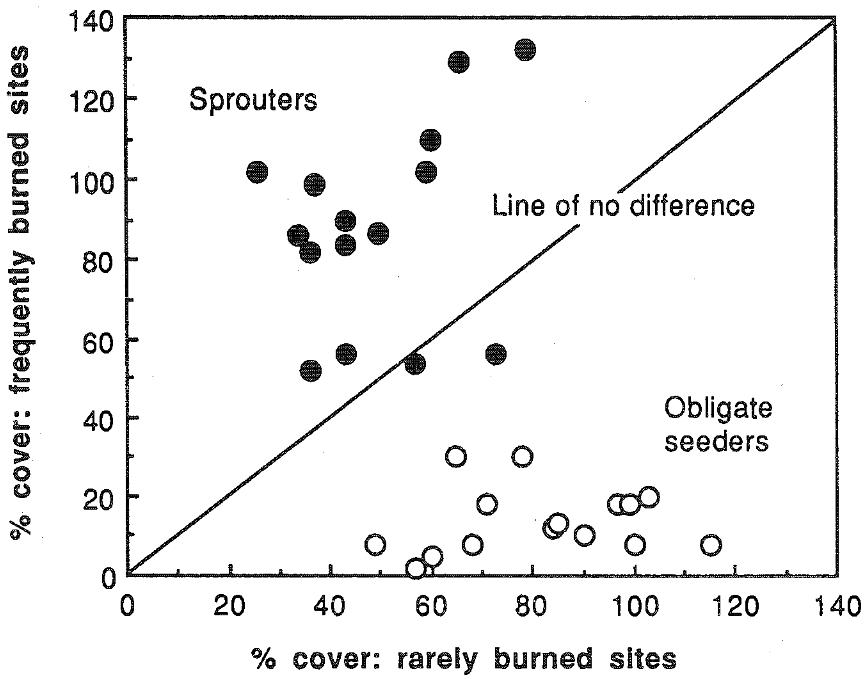
population decline or even local extinction (Bradstock and Myerscough 1981).

It is tempting to treat *B. ericifolia* as a model and use information on the life histories of other obligate seeder species (see Fig. 4) to predict that frequent fires will cause a reduction in the relative abundance of the whole group within a plant community (Fox and Fox 1986). Some support for this conclusion has come from a recent study by Nieuwenhuis (1987), who compared 25 sites rarely burned during the past 20 years with adjacent, matched sites that had burned frequently. These data show a marked reduction in the percent cover of obligate seeders and an increase in the cover of the resprouters in the frequently burned sites (Fig. 5).

Too frequent: the introduction of a flammable weed component

> Too frequent firing, by prescribed burning, to control accumulation of ground fuel can result in modification of the environment that favors the invasion of these forests by exotic plants that are better adapted to frequent firing than are the indigenous shrub species.

Figure 5. A survey of 15 matched pairs of sites burned at high and low frequency (data from Nieuwenhuis 1987) revealed differences in the percent cover of both obligate seeder and sprouter shrub species. As a group, the obligate seeders showed substantially less cover in each frequently burned site than in the paired rarely burned sites. For most pairs, sprouters performed better in the frequently burned site.



In the Mount Lofty Range, in South Australia, exotic shrubs produced a greater volume of more flammable fuel quicker than the native scrub following modification of the forest environment.

These quotations come from a paper by Cochrane (1969) in a previous Tall Timbers Fire Ecology Conference, and they illustrate a potential problem associated with too frequent fire in many ecosystems (Cochrane 1963). Bladey grass (*Imperata cylindrica*) and bracken (*Pteridium esculentum*) appear to respond in this way in the Sydney Region, producing a sward which becomes highly flammable soon after each fire (pers. obs.).

Too frequent (or too infrequent?): the ground parrot

Barren Grounds Nature Reserve was originally set aside for the protection of populations of the ground parrot (*Pezoporus wallicus*) and the eastern bristle bird (*Dasyornis brachyterus*), two threatened species of the Australian fauna, which are distributed in relatively small, disjunct populations in the few remaining areas of suitable habitat (Halliday 1978). Fires occur in the swampy sedgelands favored by the ground parrot, and its abundance appears to be related to time since fire. A fire removes ground parrots from an area and the vegetation structure and/or recovery of food plants (sedges) does not become suitable for some years (R. Jordan, pers. comm.). If left unburned, heath appears to become unsuitable for parrots after about 15 years (Meredith et al. 1984). Fires may therefore have to be introduced deliberately if an area has escaped fire for a long time.

We estimate that to satisfy a hazard-reduction objective, controlled burning would be required every three years to ensure reduced wildfire intensity and rate of spread in the highly flammable sedgeland vegetation. The imposition of a broad-scale, patchwork fuel reduction program, once contemplated by the management authority, would leave only a small proportion of the reserve suitable for parrots at any one time, thus compromising a principal management objective in order to achieve some control over intensity and behavior of a future wildfire (Whelan 1983).

Too small: the effects of herbivory

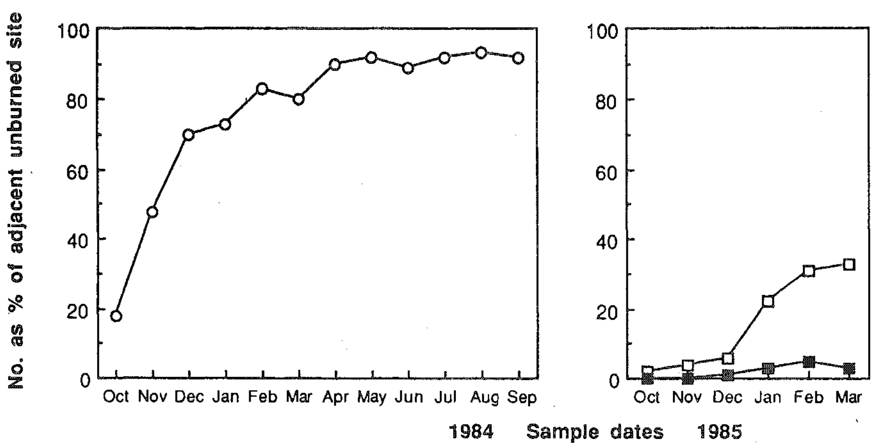
A typical hazard-reduction burning program produces fires which do not burn 100% of the vegetation. In fact, a "successful" hazard reduction burn from aerial ignition may burn about 40% of the area of the block of vegetation. Thus the vegetation actually burned is in small patches surrounded by unburned vegetation. In addition to this pattern within the burn area, blocks selected for hazard reduction burning are often small in area. A consequence of these patterns is that animals are easily able to escape the fire fronts and unburned vegetation provides refuges from which herbivores can move back into burned patches to forage. Whelan and Main (1979), for example, showed that herbivorous insects (grasshoppers) can reinvade a small burned area more rapidly than a larger burned site (Fig. 6a). What effects could this accessibility of small patches of burned vegetation to herbivores have on the vegetation?

There are numerous anecdotal reports of mammalian herbivores favoring the vegetation sprouting in newly burned areas. In fact, the role of mammals in inhibiting eucalypt regeneration after fires was pointed out by Mount (1970) in a previous Tall Timbers Conference. Whelan (1986) reported that feeding by swamp wallabies (*Wallabia bicolor*) on clumps of an herbaceous lily (*Sowerbaea juncea*) was highest at the margins of an burned area and lowest both well within the area of the burn and also in unburned vegetation (Fig. 6b).

Leigh and Holgate (1979) studied the effects of mammalian herbivores on survival and recruitment of shrub species and found a marked effect when grazing was combined with fire (Fig. 7). They warned that there was "an urgent need for research into the effects of controlled burning on the extent to which plant communities and their component species are utilized by herbivores and subsequently modified."

This warning is as apt today, because there is still very little research in this area. One reason is that it is difficult to conduct replicated experiments designed to compare the effects of herbivores in small patchy burns with their effects in large-area wildfires.

Figure 6. Invasion of herbivores into burned vegetation from an unburned edge. (a) Whelan and Main (1979) showed that densities of acridid grasshoppers in eucalypt woodland in Western Australia approached the levels observed in unburned control areas more rapidly after small patchy fires (1984, left-hand side) than after a large, widespread fire (1985, right-hand side). In addition, the increase in numbers was more rapid at the edges of the large fire (open squares) than 200 m in (solid squares). (b) Herbivory by *Wallabia bicolor* on the lily *Sowerbaea juncea* at different distances from an unburned edge after a large fire in sedgeland in southeastern Australia (data from Whelan 1986).



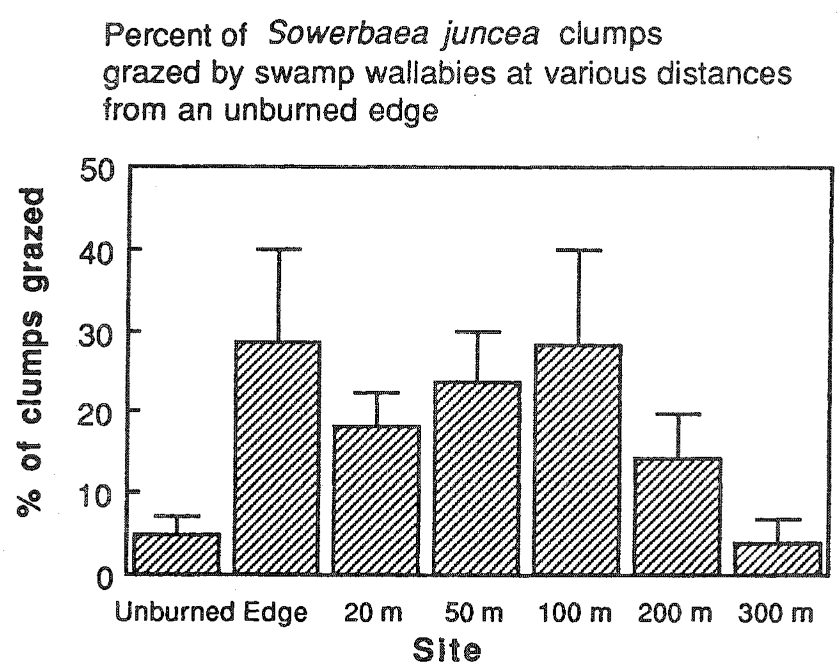
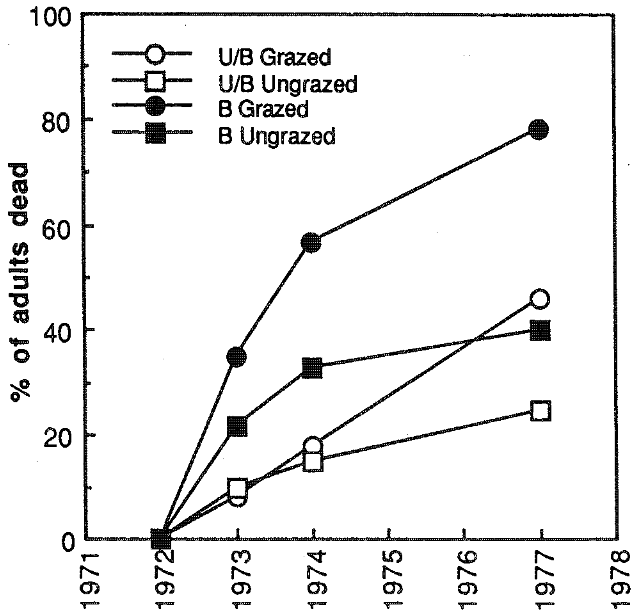
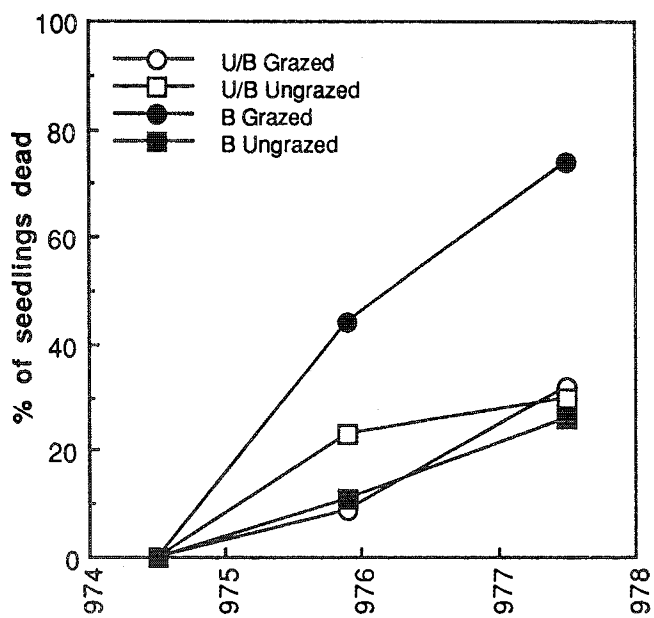


Figure 7. Mortality of both established plants (left) and seedings (right) of *Daviesia mimosoides* was greatest when herbivory was superimposed on fire (data from Leigh and Holgate 1979). Neither fire alone nor herbivory alone caused mortality rates substantially different from the unburned, ungrazed control plants.





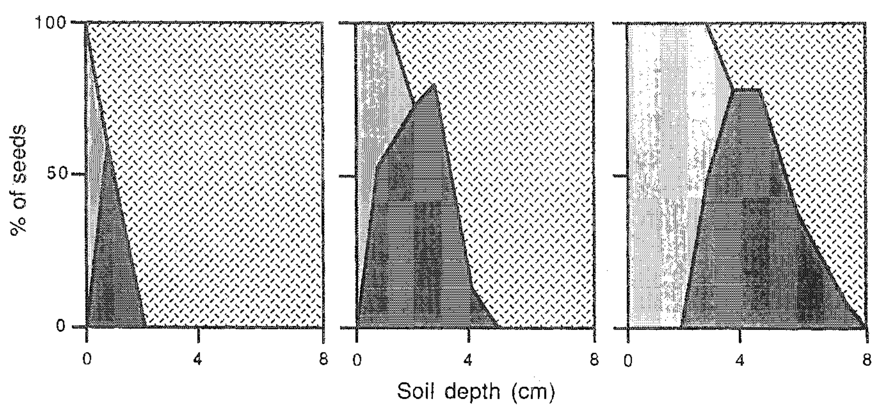
Too cool: germination of legumes

Seeds of many legume species in plant communities of the Sydney region are distributed in the soil profile by ants (Rice and Westoby 1981; Auld 1986, 1987; Auld and Myerscough 1986). Auld (1986) showed that 38% of *Acacia suaveolens* seeds were located between 0 and 5 cm below ground, 32% between 5 and 10 cm and 30% deeper than 10 cm. Like many legume species most of these seeds are in a state of dormancy, enforced by an impermeable seed coat which is broken by the heat in a fire. As heat penetration downwards through soil is poor, the peak temperature and the duration of heating by fire at the soil surface will determine how many seeds are able to germinate. Cool fires will only produce germination from the surface layer while hotter fires, although they may kill seeds on the surface, stimulate germination of a higher proportion of the seed bank (Fig. 8).

Of course, ungerminated seeds may be available for a future fire, depending on the rate of loss of seeds from this seed bank through declining viability, predation, and decay. However, if low-intensity fires occur with high frequency, killing established plants before they flower, further contributions to this seed bank will be reduced.

Shea et al. (1979) reported an interesting interaction between herbivory and low-intensity fires in relation to legume regeneration in Western Australian eucalypt forest. The fires were of insufficient intensity, in most locations, to cause substantial seed germination. However, there were localized "hot-spots" in which germination was profuse. The patchiness of the controlled fire permitted the survival of populations of herbivorous mammals which caused enormous mortality among legume seedlings in these dense patches.

Figure 8. The combined effects of fire intensity and depth of burial of legume seeds on germination (from Auld 1986). At low intensity (left-hand graph), most seeds remain in enforced dormancy (hatching), a small proportion—near the surface—germinates (dark stippling), and only those seeds on or close to the surface are killed by excessive heat (light stippling). At high intensity (right-hand graph), only seeds at great depth remain in enforced dormancy and a substantial proportion at intermediate depth escapes death by heat and germinates.



Conclusions

The case studies reviewed above point to questions which should be investigated in long-term studies. They provide indications that the prescription of a regular fire regime comprising (1) high frequency fires, (2) in the cool season, (3) of low intensity, and (4) of small area and/or patchy, will cause a shift in plant community composition towards resprouter species, introduced weeds, and species less palatable to herbivores. One reasonable conclusion is that large-area, high-intensity fires from time to time may be necessary to maintain community composition in the longterm. It is time this possibility was studied directly.

RESEARCH CONTRIBUTIONS TO MANAGEMENT—NEW SOUTH WALES

About 20 years ago, the Australian Conservation Foundation (ACF 1970) made the following statement which provided an important justification for integrating the ecological effects of fire with management decisions related to application of a fire regime (cited in Attiwill 1984):

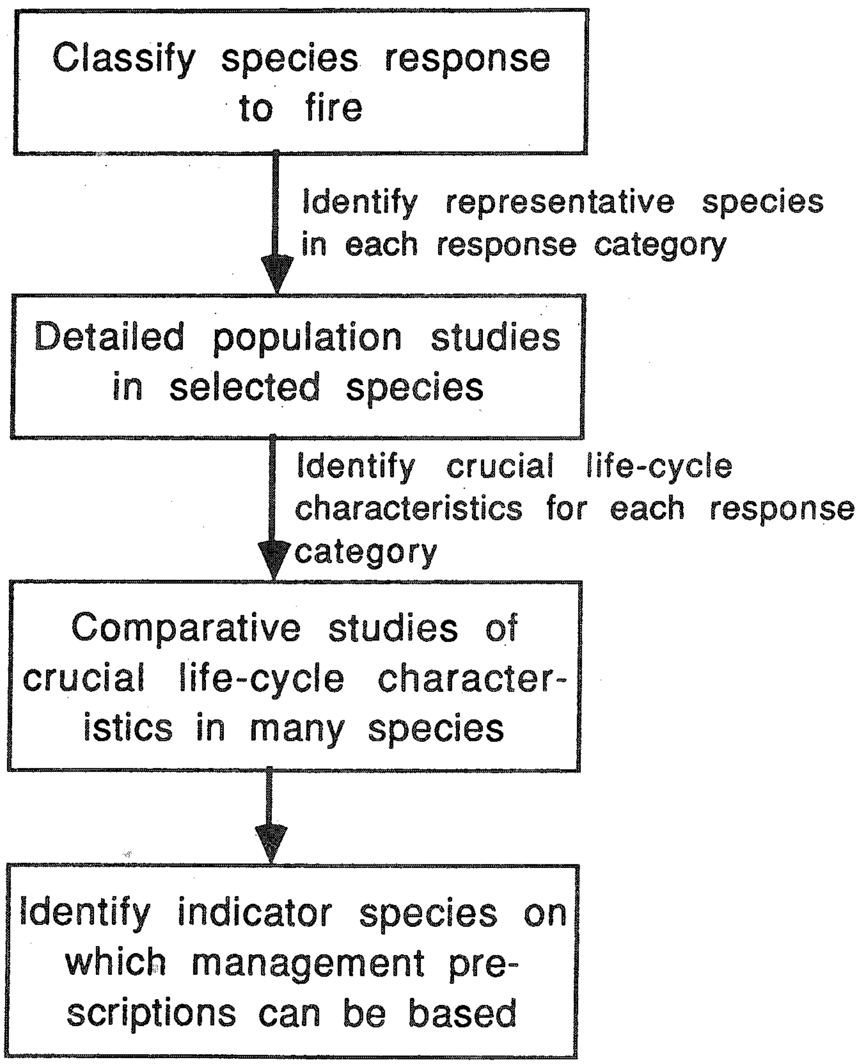
> It takes time for the results of research to percolate down to those in charge of local operations, and for procedures that have been rather rule-of-thumb, based on a subjective and rather casual judgement, to be given the precision of a scientific operation...
>
> When a continuing fire routine is imposed on a patch of vegetation, the ecological effects will in general be cumulative; and those noticeable after the first one or two fires may be a poor indication of what five or ten successive fires will bring about. When an area of forest is scheduled for control-burning, say every five years, we should surely be interested in what its condition and structure are likely to be a quarter or half a century hence; but on present knowledge we can do little more than guess.

Typical interactions between managers and researchers in the past have been along the following lines. *Researcher*: "Management does not, but should, take into account the possibilities for ecological damages caused by management practices." *Manager*: "You are the experts. Tell us what management strategies are appropriate from an ecological viewpoint, and we will do our best to implement them" (Whelan and Spencer 1983, Whelan 1989).

It should be apparent, from the case studies reviewed above, that ecological knowledge of the responses of various elements of the biota to different fire regimes is nowhere near complete enough to enable the formulation of a fire management plan for any particular ecosystem. This is true even for the plant communities of the Sydney region, perhaps the most frequently studied in Australia. Researchers are putting forward a range of <u>potential</u> ecological problems which could follow a changed fire regime in many ecosystems but are unable to identify <u>actual</u> problems in a particular situation. Thus managers must develop a research component to their management.

The necessity of conducting the research needed to make predictions about long-term changes in plant community structure and integrating this process with fire management has been recognized by the New South Wales National Parks and Wildlife Service (Auld et al. 1988). The proposed research plan (Fig. 9) is based upon detailed research into the population responses of selected species to fire, focussing on key life-history stages. From this basic information, computer models will be used to predict population and community changes under a variety of possible fire regimes.

Figure 9. The research component to devising a prescription fire regime in national parks in New South Wales, Australia (from Auld et al. 1988).



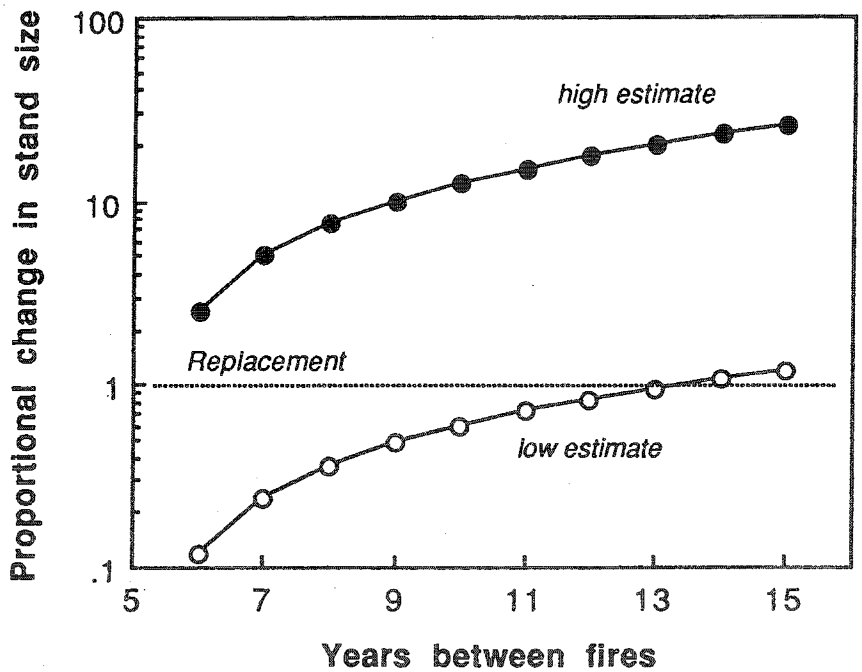
Bradstock and O'Connell (1988) provided a good example of the potential for this approach. Five crucial aspects of the demography of obligate seeders were identified: (1) time taken to first reproduction, (2) post-fire seedling establishment, (3) size of the prefire seed bank, (4) survivorship from seedling establishment to adults, and (5) seedling establishment in unburned conditions. Estimates of these factors were obtained over a relatively short time period by a combination of (1) observations of stands of various ages since last fire and (2) longitudinal study of individual seedlings and adult plants after wildfires and experimental fires. This information was then used to calculate trends in plant densities under various fire frequencies. The numbers of stored seeds can be counted readily in any stand. Then the estimates of proportion germinating, proportion of germinated seeds becoming established seedlings, proportion of established plants surviving to the time of the next fire, and mean number of seeds accumulated per plant by that time can be used to predict future stand sizes after any number of fires at any frequency. In Bradstock and O'Connell's study, application of this approach produced the conclusion that at the highest rates of seedling emergence and survivorship local densities would increase in the second "generation" at all likely interfire periods (6 years to 15 years). However, at the lowest rates of emergence and survivorship observed in the field, populations would decline unless the interfire period exceeded 12 years (Fig. 10).

This approach can be extended to resprouters, by including data on "stage-specific" mortality rates of already-established individuals in the population—young juveniles, juveniles, and adults. This makes projections more complicated, of course, but high fire-frequency (every 5 years) would apparently cause a decline in the population density of resprouters as recruitment was inhibited and mortality of established plants occurred (Bradstock and Myerscough 1988).

Potential Problems With Projections

The trend towards including basic research on responses of plant populations to fire in a fire-management context is clearly necessary and should be developed much further. However, we are cautious about the incorporation of computer aided modelling of population changes under a variety of hypothetical fire regimes because we believe it will prove appealing to many organizations for the precision the approach appears to carry. This situation may tempt managers to complete the research component of their management at the stage of the predictive model without continuing at least a monitoring program to determine its accuracy. Here we point to some components of the responses of a biota to fire which probably vary in a number of ways and, therefore, question the adequacy of any projection of long-term change based on a short-term empirical study, especially when estimates of temporal trends come from a "chronosequence" of sites that are of different ages since the last fire (Muston 1987).

Figure 10. The effects of different times between fires on the population size of a stand of *Banksia ericifolia* in New South Wales, based on a model of the dynamics of accumulation of a seed bank over time since last fire, seedling establishment and survivorship after fire (from Bradstock and O'Connell 1988). The high estimate used high observed levels of seedling establishment and survivorship (e.g. fertile site, good post-fire climatic conditions) while the low estimate used low establishment and survivorship figures.



Choice of "indicator species"

Benson (1985, see Fig. 4) found considerable variation among obligate seeder species, and among sites within a species, with respect to time to first flowering. Nieuwenhuis (1987) presented evidence that some species of obligate seeder were at risk of local extinction in frequently burned sites while others may be at risk in infrequently burned sites. Knowing the extent of variation of this sort is important in order to avoid inaccurate extrapolation from one study species to a range of others. Moreover, a fire frequency which sustains a species at one site may disadvantage it at another. This illustrates the need for more information on a wider range of species to enable suitable, representative species to be selected for more detailed study. In the case of plants, life history information on time to first flowering after fire, capacity to resprout vs. fire intensity, and instances of interfire recruitment are all needed for a range of species.

We suggest the development of a register of species-specific data relating to survival strategies and maturation times of recruits. Such a register could be established by a search of the published and "grey" literature relating to fire ecology, and contributions made by researchers, managers, conservation groups, etc. Regions and/or species for which important information is absent could be identified from time to time and made the focus of specific research. The potential for this approach to work, at least in Australia, has been shown by the *Banksia Atlas* (Taylor and Hopper 1988), which used volunteers in a nationwide project designed to produce a data bank of species distributions, plant community associations, environmental correlates, pollinators, and responses to fires.

An inadequate data base

An enormous amount of time and effort is required to achieve the information needed about various demographic processes in relation to fire, as indicated in the study by Bradstock and O'Connell (1988). Inference about population changes from a more limited set of data can produce erroneous projections. For example, as mentioned above, high densities of legume seedlings are frequently observed after high intensity fires but not after those of low intensity (Shea et al. 1979, Auld 1986) and it is tempting to infer that high intensity fires are necessary to maintain populations. However, Muston (1987) found that an experimental fire in a single Hawkesbury Sandstone catchment produced substantial variation in fire intensity. Germination of some shrub species, especially legumes, was observed to be denser in the high intensity patches than in the low intensity patches, as might be expected. However, during the 13 years for which community changes were measured, the initially high seedling density declined to product adult densities at about prefire levels. Shea et al. (1979) also found that seedling survivorship in patches of high fire intensity declined markedly due to herbivory, to the extent that *Acacia pulchella* virtually disappeared except in areas fenced to exclude mammals.

Importance of unpredictable episodic events

Many studies of the effects of fire on vegetation in the Sydney region have commented upon the importance of post-fire climate as an influence on recruitment into plant populations (e.g. Bradstock and Myerscough 1981, Clark 1988). Two aspects of this observation are relevant. First, large-scale germination does not necessarily imply massive recruitment into a population. Second, it poses the question of to what extent a change in population size or community structure perceived after a single fire can be indicative of a directional trend. This is especially relevant if the data which produce figures for rates of seedling establishment, survivorship, and seed accumulation to be used in a model come from studies on just one or a few fires. Walters and Hilborn (1978) explored the problem of fitting ecological research to management in a system with a substantial amount of inherent, stochastic variability.

Spatial heterogeneity and recolonization

The various components of a fire regime are not entirely independent. For example, as fires are ignited with greater frequency, they are likely to become less intense, on average, and more patchy, because fuel loads do not have time to build up between fires. Even in high-intensity wildfires, topographic discontinuities can provide a patchiness which provides a refuge for individual plants or animals. For example, in the Hawkesbury Sandstone plant communities of the Sydney area, sheets of exposed sandstone as illustrated in Figure 2(b) commonly protect individuals of the obligate seeder, *Banksia ericifolia*. Benson (1985) concluded from this that frequent burning may not eliminate species such as this because of bouts of reinvasion from less-frequently burned refuges. Nieuwenhuis (1987) argued that the finding mentioned above, that some obligate seeder species were susceptible to frequent fires while others were susceptible to lack of fire, might be explained by different capacities for colonization from infrequently burned refuges. A categorization of species into obligate seeder and sprouter strategies is, in itself, an inadequate basis for extrapolation of effects of fire.

Interaction effects

The challenges of determining simple effects of fire on populations of any element of the biota are substantial, without considering the many possible interaction effects, especially herbivory. As many authors have stated, the impact of herbivores on plant communities may not be readily apparent. However, exclusion of herbivores by fences frequently reveals a substantial effect (Crawley 1983). It is becoming obvious that fire can cause a great magnification of the effects of herbivory on vegetation, partly because of the enhanced susceptibility of individual plants at this time. As Leigh and Holgate (1979) stated: "We offer tentatively a word of warning against any sweeping statements as to the pattern of successional changes after fire. . . in the absence of a clear understanding of the interacting effects of grazing."

THE FUTURE

At a time when ecologists as a professional group, are engaging in an examination of their social responsibilities (McComb 1989, Whelan 1989, Davis et al. 1988), we foresee a greater interaction between researchers and managers. Clearly management decisions will be made now—with or without the input of researchers in ecology. We have argued above that the hazard-reduction burning procedures developed for protection of tree species in commercial forestry are readily transferred to other land areas, and there is considerable and constant pressure to do so. The fact that the potential ecological effects of changed fire regime are very complex and difficult to predict makes it difficult to argue against widespread adoption of this hazard-reduction technique. It is easier to grapple with and solve the technological aspects of smoke control and protection of neighbors than to decide on the "right" fire regime for an area. However, unless the ecological research is addressed, we risk modifying many plant communities and compromising some of the management objectives in many areas, especially national parks.

The trend of basic ecological research now being conducted by management authorities, as described in this paper, is encouraging but can only remain limited because of competing, demands on resources, and time available to management staff. The acquisition of ecological information and testing of management strategies cannot be streamlined by application of results obtained in one region to other regions because variation in the biota, geography, and climatic and edaphic conditions make many results site specific. Involvement of researchers is needed more than ever. The collaboration must be more substantial than the situation common in the past, such as: "you may have access to sites" and "we agree to provide a copy of the final publication." Experiments that are properly designed, adequately replicated and clearly analyzed must be conducted on a large scale and over a long time span. They must therefore parallel management and the results must be readily available to modify fire management programs.

Based on our experience in the Sydney and Wollongong areas, we see two major research challenges for the near future. (1) The establishment and monitoring of long-term, replicated studies, with various aspects of fire regime (initially season and frequency) carefully manipulated, in order to test the predictions of community change based on the population dynamics models for a few selected species. Such monitoring will itself provide new information of value to managers. (2) Experimental investigation involving large-area and high-intensity fires as treatments in replicated studies, of ways in which patchiness and/or extent of fire can alter plant community composition via herbivores.

Finally, we foresee major challenges to the development of refined management strategies. Research may well indicate that high-intensity, large-area fires are necessary from time to time to maintain communities and particular species disadvantaged by other fire regimes. The techniques of fire control will need to be developed to such an extent that such a prescription fire can be contained. However, many areas currently being managed using fire are too small and too isolated to permit fires of large area or to risk a prescription fire of high intensity escaping. How can the effects of these sorts of fires be mimicked in such a situation? As an example of the problem and a possible solution, herbivory by marsupials following patchwork, hazard-reduction fires was so great in a small coastal plain reserve in Western Australia (B. T. Clay, pers. comm.) that attempts were made to use electric fencing to exclude most large herbivores from a recently burned block for about one year after fire. By this time it was judged that both resprouting plants and seedlings, especially of legumes, would be sufficiently tolerant of grazing.

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