Forum: Issues, Management, Policy, and Opinions

Human Fires and Wildfires on Sydney Sandstones: History Informs Management

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ABSTRACT

There is a concept in fire ecology that some natural (pre-European) fire regimes were dominated by infrequent high intensity fires ignited by lightning. In Australia, some ecologists extend this to most or all ecosystems across the landscape. They regard contemporary human burning or prescribed burning as an unnatural disturbance that threatens biodiversity. Their particular concern is the potential extinction of slow maturing obligate seeders by frequent fire. However, a completely different picture emerges from study of Australia's ecological history and prehistory. There is ample evidence that Australian vegetation was shaped by thousands of years of frequent mild burning by Aborigines. Infrequent, high intensity lightning fires affected only small areas of wet forests in refuges that were physically protected from mild fires. We present a case study of ecosystems on the Sydney sandstones to demonstrate that a regime of infrequent high intensity wildfires since European settlement has caused structural changes and reduced spatial diversity. This has put many fire dependent plants at a competitive disadvantage and increased their susceptibility to disease.

RESUMEN

En ecología del fuego se plantea que algunos regímenes de fuego naturales (pre-europeos) fueron dominados por incendios poco frecuentes de alta severidad causados por rayos. En Australia, esta idea ha sido aplicada por ecólogos y ecólogas a la mayoría de los ecosistemas en el paisaje, quienes consideran que los incendios de origen humano y las quemas prescritas contemporáneas son disturbios no naturales que amenazan a la biodiversidad. Su principal preocupación es que los incendios frecuentes pueden causar la extinción de plantas semilladoras obligadas de crecimiento lento. Sin embargo, estudios ecológicos de la historia y prehistoria australiana muestran una imagen completamente diferente. Existen evidencias de que la vegetación australiana se ha formado a lo largo de miles de años de quemas frecuentes y de baja severidad iniciadas por grupos aborígenes. Los incendios de alta severidad y baja frecuencia causados por rayos han afectado solo áreas pequeñas de bosques húmedos en refugios que estuvieron físicamente protegidos de los incendios de baja severidad. Presentamos un estudio de caso de ecosistemas en las areniscas de Sidney para demostrar que los regímenes de incendios de baja frecuencia y alta severidad, a partir de la colonización Europea, han causado cambios estructurales y reducción de la diversidad espacial. Esto ha puesto a muchas plantas dependientes del fuego en desventaja competiti-

We argue that biodiversity, ecosystem health, and fire safety are threatened by lack of frequent mild fire. Ecological theory should build on ecological history. Australia is fortunate in having comprehensive historical records of Aboriginal burning against which paleoecological data can be calibrated. We emphasize the importance of using historical information to interpret ecological studies and inform fire management.

va, incrementando su susceptibilidad a enfermedades. Argumentamos que la biodiversidad, salud y resistencia de los ecosistemas se ven amenazadas por la falta de incendios de baja severidad. La teoría ecológica debe basarse en la historia ecológica. Australia tiene la fortuna de contar con registros completos de las quemas aborígenes para calibrar los datos paleoecológicos. Enfatizamos la importancia del uso de información histórica para interpretar estudios ecológicos y proveer información para manejo del fuego.

Keywords: Aborigines, biodiversity, European settlement, fire regimes, history, prehistory, sandstone, Sydney, vegetation change, wildfires

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INTRODUCTION

Many Australian ecologists have assumed that ecosystems showing little evidence of human activity (usually characterized as "disturbance") represent the natural (pre-European) state (e.g., McElhinney *et al*. 2006, Gibbons *et al*. 2008, Killey *et al*. 2010). This hypothesis portrays stands of native vegetation that have been dramatically altered as a consequence of more than a century of fire suppression as benchmarks of natural conditions. In fire ecology, the assumption has led to conclusions that prescribed burning reduces densities of woody plants and quantities of litter, fallen timber, and soil nutrients below natural levels, and that this threatens biodiversity (e.g., Morrison *et al*.1996, Henderson and Keith 2002, Tasker and Bradstock 2006, Christie and York 2009, Tasker *et al.* 2011).

This assumption implies that the natural (pre-European) fire regime was one of infrequent (at least decadal), extensive, high intensity wildfires ignited by lightning, and that the natural vegetation was mostly thickly wooded. However, prehistoric and historic records of fire regimes and vegetation contradict this. For example, Matthew Flinders (1814) described thickly wooded vegetation and evidence of infrequent high intensity lightning fires on the uninhabited Kangaroo Island in 1802. He contrasted this environment with continental Australia where human fires were prevalent.

The view of a thickly wooded Australian landscape shaped by infrequent and intense wildfires is unsustainable for two reasons. Firstly, it is totally inconsistent with historical records of Aboriginal fire regimes and vegetation (e.g., Tench 1793; Flinders 1814; Mitchell 1839, 1848; Curr 1883; Howitt 1891; Pyne 1998; Gammage 2011); secondly, it ignores the widespread woody thickening that occurred after Aboriginal culture was disrupted and frequent mild fires no longer maintained the Australian landscape (Mitchell 1848, Howitt 1891, Gammage 2011).

Dense and homogeneous stands of trees or woody shrubs created by post-European management have been studied as if they were natural ecosystems, and some fire management guidelines have been devised to maintain these artificial assemblies and structures. Unnatural processes have been described as if they were natural. For example, Cohn *et al*. (2011) described the response of unnaturally dense stands of *Callitris* (*Callitris glaucophylla* Joy Thomps. & L.A.S. Johnson) to unnaturally severe fires as though it were a natural process. In fact, these conifers were attuned to occasional low intensity fires that killed seedlings and maintained the health of scattered mature trees with thick, insulating bark that protected them from damage by quick moving fires in grassy fuels (Jurskis 2009, 2011*a*).

The argument (e.g., Mooney *et al.* 2001, 2011) that Australian Aborigines did not burn frequently and extensively because sustained high levels of biomass burning were not evident as charcoal in sediments post-dating Aboriginal occupation cannot be sustained. The prehistory of fire in Australia can only be resolved by calibrating sedimentary charcoal records against historical records. Charcoal deposition increased markedly at the time, about 40 000 years ago, that Aborigines occupied Australia (Mooney *et al*. 2011: Figure 2); after the demise of the Aboriginal population on Kangaroo Island about 2500 years ago (Singh *et al*. 1981); and after European settlers disrupted Aboriginal culture on the mainland (Howitt 1891, Mooney *et al*. 2011). Charcoal deposition was reduced after extensive prescribed burning was reintroduced by forest managers in the mid-twentieth century (Jurskis *et al.* 2003, Mooney *et al.* 2011). Increased deposition of charcoal was clearly associated with intense fires in heavy accumulations of fuel (woody biomass), whereas reduced deposition was associated with long term Aboriginal burning and broad area prescribed burning by forest managers.

The reported negative impacts of frequent mild burning (at intervals less than about ten years) have been based on comparisons of frequently burnt vegetation against infrequently burnt or long unburnt areas inappropriately designated as controls (Turner *et al*. 2008, Jurskis *et al*. 2011). Much of this work has focused on non-resprouting, bradysporous shrubs (seeds retained for long periods in aerial, woody fruits unless released by fire) on sandstone formations around Sydney (e.g., Keith *et al*. 2002: Figure 17.2a). We examine this work in the context of historical information about vegetation and fire regimes in the area.

THE FIRE HISTORY OF SYDNEY'S SANDSTONE VEGETATION

When Europeans settled at Sydney in 1788, their agricultural activities were virtually confined to the Cumberland Plain, which is encircled by large areas of Triassic sandstones. These rugged and barren areas have remained largely undeveloped and now form an extensive system of national parks including the Blue Mountains to the west, most of the land between Sydney Harbour and the Hawkesbury River to the north, and Royal National Park immediately south of Sydney. The consequently long interface between urban and wildland around Australia's largest city has led to extensive debate about the fire history, ecology, and management of Sydney's wildlands.

Detailed observations of Aboriginal culture in this region were made by Captain Lieutenant Watkin Tench (1793) during the first four years of European settlement at Sydney Cove (1788–1791). Tench was an officer in the second rank of the new colony's military department. He reported that Aboriginal people carried fire wherever they went, noting that "they always, if possible, carry a lighted stick with them, whether in their canoes or moving from place to place on land." He saw Aborigines "perpetually setting fire to the grass and bushes" and noted that "it is a very common custom" for "the Indians in their hunting parties" to "set fire to the surrounding country". Aborigines used fire for warmth, cooking, hunting, signaling, lighting their way, managing vegetation and fauna, and in celebration as well as in conflict (e.g., Tench 1793; Flinders 1814; Mitchell 1839, 1848; Curr 1883; Howitt 1891; Gammage 2011). Fire was integral to the mental and material existence of Australian Aborigines (Pyne 1998).

On 11 April 1791, Tench left Rose Hill (now Parramatta) with a party of exploration. Each member of the party except Governor Phillip carried about twenty kilograms of bulky equipment and provisions. Once they reached the sandstone country (at what is now known as North Rocks), the terrain became, "very bad, being full of steep barren rocks, over which we were compelled to clamber for seven miles". However, the only references by Tench to difficulties occasioned by vegetation were along the Hawkesbury River where they were "plagued and entangled … stung … with nettles and ridicule," (by their Aboriginal guides) "and shaken nigh to death" by tripping over obstacles.

Once more in rocky sandstone country with "nothing but trees growing on precipices", Tench "saw a tree on fire here and several other vestiges of the natives." Scrambling to the top of a sandstone mountain "with infinite toil and difficulty", Tench had an extensive view "in almost every direction, for many miles." Governor Phillip named this "pile of desolation" Tench's Prospect Mount (Tench 1793).

The "infinite toil and difficulty" faced by Governor Phillip's party in scrambling up Tench's Prospect Mount was as nothing compared to the task that would confront them in the current dense vegetation (Figure 1). Furthermore, the toil would be wasted because the party's objective—Richmond Hill (now Enfield Hill)—is no longer visible due to the thick growth.

Gregory Blaxland (1823) led the first European crossing of the Blue Mountains in 1813. He described thickets of "brushwood" that impeded the packhorses. However, in unknown territory, a few men were able to clear and blaze a track through this tall shrubland for four heavily laden packhorses at the rate of one mile (1.6 km) per hour, suggesting that the shrubs were not very dense, and certainly not as dense as they are today.

Surveyor General Thomas Mitchell (1839) observed that "no vegetable soil is formed" on sandstone in New South Wales because "conflagrations take place so frequently and extensively … as to leave very little vegetable matter to return to earth." Travelling the Great Northern Road, Mitchell described the country between Parramatta and the Hawkesbury River thus:

Figure 1. Dense undergrowth on the approach to the summit of Tench's Prospect Mount. Note large dead banksia in left foreground. No large live banksias were present.

> *… no objects met the eye except barren sandstone rocks, and stunted trees. With the* banksia [Banksia *spp.*] *and* xanthorhaea [Xanthorrhoea *spp.*] *always in sight … The horizon is flat ...*

Mitchell had surveyed the continuation of the road through the sandstone country north of the river, and recounted that:

> *... the whole face of the country is composed of sandstone rock, and but partially covered with vegetation. ... on many a dark night … I have proceeded on horseback amongst these steep and rocky ranges, my path being guided by two young boys belonging to the tribe who ran cheerfully before my horse, alternately tearing off the stringy bark which served for torches, and setting fire to the grass trees (*xanthorhaea*) to light my way.*

Today, Mitchell's Aboriginal assistants would not be able to run "cheerfully before" his horse, lighting grasstrees because the vegetation is too thick and fully grown grasstrees are rare as are large banksia trees. In fact, anyone would have great difficulty riding a horse through the current vegetation, even in broad daylight (Figure 2).

Figure 2. This is the forest type and locality that Mitchell traversed on horseback in the dark of night and described in daylight as follows: "no objects met the eye except barren sandstone rocks, and stunted trees. With the banksia and xanthorhaea always in sight … the whole face of the country is composed of sandstone rock, and but partially covered with vegetation".

When Charles Darwin travelled the road blazed across the Blue Mountains by Blaxland's party, he described "scrubby trees of the never-failing Eucalyptus family". Clearly the patches of shrubland made little impression. When he descended to the granite country of the central tablelands he noted "the trees were both finer and stood farther apart; and the pasture between them was a little greener and more plentiful" (Darwin 1845).

Though the sandstone country was not generally thickly wooded, thickets occurred in some rocky or sheltered sites. Mitchell noted that after European settlers occupied their kangaroo grounds, the displaced Aborigines:

> … *were compelled to seek a precarious shelter amidst the close thickets and rocky fastnesses which afforded them a temporary home, but scarcely a subsistence … I knew this unhappy tribe, and had frequently met them in their haunts. In the prosecution of my surveys I was enabled to explore the wildest recesses of these deep mountainous ravines, guided occasionally by one or two of their number*.

Tench and Judge Advocate David Collins recorded the first European observations of fire behavior under drought and extreme weather conditions at Sydney. Aboriginal fires were burning in bushland northwest of Rose Hill (Parramatta) on 10 and 11 February 1791 under extreme temperatures (>40 °C) and searing northwesterly winds, conditions that caused fruit-eating bats and parrots to drop dead from the sky. However, the fires did not affect the settlement (Tench 1793, Collins 1798). There was another "blow up day" (a day when high temperatures, low humidities, and strong winds can cause extreme fire behavior) on 5 December 1792 when a grass fire at Sydney burnt one house and several fences before being controlled (Collins 1798). Extensive fires at Parramatta and Toongabbie on the same day also had relatively minor impacts. They were thought to be controlled until a firebrand from the crown of a tree ignited a spotfire on a thatched roof, leading to the destruction of a hut, outbuildings, and a stack of wheat (Collins 1798). The minimal impact of these fires, burning under extreme conditions, demonstrates that they were generally burning in light, discontinuous fuels, and thus did not attain high intensity (e.g., Jurskis *et al*. 2003).

MODERN HISTORY AND ECOLOGY OF SYDNEY SANDSTONE VEGETATION

After disastrous fires around the mid-twentieth century, Australian foresters introduced broad area prescribed burning, including aerial ignition, as a major facet of fire management (Jurskis *et al.* 2003). Ecologists began to raise concerns about the potential environmental impacts of prescribed burning, and in 1976 the Scientific Committee on Problems of the Environment initiated an international fire ecology project (Gill *et al*. 1981). In this project, Gill (1981) reviewed responses to fire of Australian plants. He suggested that plants be classified as sprouters or seeders and their life cycles analysed in the context of fire regimes to assess their likely persistence. This suggestion was enthusiastically adopted by many ecologists, particularly in regard to non-resprouting bradysporous shrubs, which form a major component of Sydney's sandstone vegetation.

The nub of their concern was that burning at intervals shorter than the time taken for these shrubs to develop from seedlings to sexual maturity would eliminate them, reducing biodiversity (e.g., Benson 1985, Bradstock and O'Connell 1988, Cary and Morrison 1995, Keith 1996, Keith *et al*. 2002). Dangerous fuel loads were found to accumulate within two to four years after fire, leading Morrison *et al*. (1996) to suggest that fuel reduction burning was incompatible with conservation of biodiversity. Keith *et al.* (2002) claimed that Siddiqi *et al.* (1976) had "demonstrated" local extinctions by frequent fires. However, Siddiqi *et al.* (1976) actually reported that a "fierce" wildfire eliminated some plants from a few small plots where they had been present as seedlings before the fire, whilst the same species regenerated close by, within the fire perimeter, in a more sheltered plot where they had been present as mature plants. Thus the purported extinctions (Keith *et al*. 2002) occurred at a minutely small scale and could be more aptly described as reinstatement of the natural species pattern.

Another study found that obligate seeders produced more seeds under a regime of short fire intervals (three or four years) than under longer intervals between fire, whilst resprouting shrubs showed the opposite response, and resprouting trees were unaffected (Knox and Morrison 2005). Knox and Morrison (2005) speculated that there may be rapid selection for early maturity of obligate seeders in fire prone environments.

A number of studies demonstrated that short intervals between fires disadvantaged large shrubs and favoured smaller shrubs or herbs (e.g., Siddiqi *et al.*1976, Cary and Morrison 1995, Morrison *et al*. 1995, Bradstock *et al*. 1997) and grasstrees (*Xanthorrhoea resinosa* Pers.; syn. *X. resinifera* Sol. ex C.Kite E.C.Nelson & D.J.Bedford) (e.g., Tozer and Bradstock 2002, Tozer and Keith 2012). Not surprisingly, plants' responses to fire varied with growth stage (e.g., Siddiqi *et al.* 1976) as well as with fire intensity (Bradstock and Myerscough 1988). It also emerged that mediation of interspecific competition by fire regimes was equally or more important than individual species responses to direct physical impacts of fire (e.g., Bradstock *et al*. 1997, Tozer and Bradstock 2002, Tozer and Keith 2012).

It is indisputable that the time between fires can influence the abundance of particular species and consequently the floristic composition of the vegetation (e.g., Bradstock and O'Connell 1988; Cary and Morrison 1995; Morrison *et al.* 1995, 1996; Bradstock *et al*. 1997). Bradstock and O'Connell (1988) predicted that densities of large shrubs on Sydney's sandstones would increase if fires occurred at fifteen to thirty year intervals, and their prediction was found to be correct by retrospective studies (e.g., Conroy 1996). There was no evidence that a reduction in density of some species by frequent prescribed burning would lead to local extinctions and reduced biodiversity. Cary and Morrison (1995) reported that frequent, intense fires (intervals less than ten years, understory completely destroyed across at least five hectares) reduced species richness, whereas Morrison *et al*. (1995) found that this regime favoured ten small plants and disadvantaged six large shrubs. Morrison *et al*. (1996) found that, of seven plants whose abundance was affected by fire frequency, the least abundant across all sites were two plants favoured by frequent fires (less than seven years), and one of these species was not found on sites with longer fire intervals (Morrison *et al*. 1996: Table 2).

Bradstock *et al*. (1997) concluded that frequency of fires affected floristic composition but not species richness. Frequent fires at short intervals (one or two years) reduced the density of seven shrubs and increased the density of one grass. The most common shrub in the area was the most reduced. Bradstock *et al*. (1997) emphasized the highly heterogeneous nature of site effects on fire regimes and vegetation, and that it was difficult to extrapolate conclusions from fine scale studies to the landscape scale.

Grasstrees were a prominent component of Sydney's sandstone vegetation at the time of European settlement (Mitchell 1839), and although still common, are suffering decline as a consequence of modern fire regimes, competition from large shrubs, and disease associated with infection by *Phytophthora cinnamomi* Rand (Tozer and Bradstock 2002, Regan *et al*. 2011, Tozer and Keith 2012). Tozer and Bradstock (2002) found that fully grown live grasstrees were virtually absent from patches of large shrubs, although there were many dead stems, "consistent with suppression by overstorey species".

Regan *et al*. (2011) sampled the demographics of grasstrees and *Phytophthora* under the recent wildfire regime. They considered that grasstrees were threatened by an adverse fire regime as well as by the fungal pathogen. Simulated populations of grasstrees declined in the long term under all fire management scenarios (burning at 5 yr, 12 yr, 20 yr, and 30 yr intervals with and without wildfires and total fire exclusion), even in the absence of disease (Regan *et al*. 2011). Tozer and Keith (2012) reported a local extinction of grasstrees after a 17 year interval between fires. They found higher mortality of grasstrees with less frequent fire because of competition from large shrubs, and they considered that presence of *Phytophthora* would exacerbate the effects of competition.

The endangered broad-headed snake (*Hoplocephalus bungaroides* Wagler), is thought to be extinct in sandstone vegetation north of Sydney (Pringle *et al*. 2009). Remotely sensed chronosequences in sandstone woodlands to the south revealed that its habitat of bare exfoliated sandstone, critical for thermoregulation, was substantially reduced between 1941 and 2006 as a consequence of shading by encroaching shrubs under a wildfire regime (Pringle *et al*. 2009).

The aforementioned ecological studies have assessed the role of recent fire history in shaping ecosystems, but they have largely neglected to assess changes in fire regimes and biota consequent to European settlement. However, records of charcoal deposition in a lagoon within Royal National Park were used to infer long term fire history. Mooney *et al*. (2001) found evidence of many fires during the previous seven decades but of only one "conflagration" during the 1600 years before European settlement. This led them to suggest that either Aborigines did not burn much or they burnt in a way that delivered little charcoal. Mooney *et al*. (2001) concluded that "the idea of the ubiquitous use of fire by Aboriginal people should be further, and critically, analysed".

In contrast, Clark and McLoughlin (1986) presented historical evidence that Aborigines burnt Sydney's sandstone vegetation frequently and that less frequent fire after European settlement caused woody thickening and upslope expansion of gully vegetation at the expense of groundcover plants. Conroy (1996) analysed the fire history of Ku-ring-gai Chase National Park between 1943 and 1994. He concluded that wildfires were more frequent and less intense prior to 1970, after which strategic burning and fire suppression were introduced. After 1970, reduced frequency and increased intensity of fire resulted in increased cover of woody shrubs that impedes bushwalkers, shades out some attractive small flowering plants, and reinforces a regime of high intensity fires (Conroy 1996).

The significance of the change in fire regimes and vegetation over the longer term can be appreciated by comparing the situation on blow up days under Aboriginal management against the current situation. Fires on blow up days in 1791 and 1792 caused little damage to settlements at Parramatta and Sydney, and were easily controlled (Tench 1793, Collins 1798). In contrast, fires under similar conditions in January 1994 (Speer *et al*. 1996: Figure 3) were mostly uncontrollable, burning more than thirty thousand hectares around Sydney, claiming hundreds of houses and three lives despite the efforts of a well-equipped army of firefighters (NSW Rural Fire Service 1998).

The difference in 1994 was that firestorms developed in the dense, three dimensionally continuous fuels produced by modern mismanagement of the native vegetation on sandstone surrounding Sydney (e.g., Figure 1). The fire storms caused showers of embers and long distance spotting of fires. For example, a run of fire that claimed human lives spotted 800 metres across a major watercourse (Hurditch and Hurditch 1994). However, Conroy (1996) listed four localities where runs of these fires under extreme weather conditions were effectively contained as a result of prior hazard reduction burning.

DISCUSSION

It is clear that Aboriginal burning maintained Sydney sandstone vegetation in a generally very open condition. Tench, Mitchell, Darwin, and others described vastly different vegetation to that currently occurring on sandstone around Sydney. Explorers systematically and meticulously recorded impediments to travel and visibility because it was a large part of their 'job' (e.g., Jurskis 2009, 2011*a*). Where they made no such records, there were clearly no such impediments to be recorded.

Mooney *et al*. (2001) used paleological data on charcoal accumulation to question the historical record. Physical records such as charcoal deposits (e.g., Mooney *et al*. 2001, 2011) or fire scars on trees (e.g., Banks 1989, von Platen *et al.* 2011) have often been misinterpreted as providing a complete prehistory of fire when, in fact, mild fires in open vegetation burn relatively low quantities of mostly fine and herbaceous fuels, leaving little charcoal or scarring (e.g., Burrows *et al*. 1995 , Mooney *et al*. 2011, Jurskis and Underwood 2012). Aboriginal burning was ubiquitous and prehistory shows that, after the period when the continent was initially occupied, subsequent burning delivered little charcoal (e.g., Mooney *et al*. 2011: Figure 2). Interpretation of charcoal in sediment cores should be informed by historical observations. Taken together, paleological and historical records indicate that Aborigines altered vegetation pattern and structure using high intensity fires when they originally occupied Australia, after which they maintained the new pattern using frequent mild burning. Following the initial peak in biomass burning, there was a sustained reduction (e.g., Mooney *et al*. 2011: Figure 2) as dense woody vegetation was restricted to physical refugia (e.g., Singh *et al*. 1981, Kershaw *et al*. 2002).

McLoughlin (1998) inferred the Sydney region's early European fire history using only individual records that identified the date. She found 31 records between 1788 and 1845 (an average of one fire somewhere in the region every two years). The more general observations of explorers and settlers indicate that fires were very common, so that specific fires were unremarkable unless they were damaging or had been set maliciously. There were certainly many more fires than those listed by McLoughlin (1998) (e.g., Tench 1793, Mitchell 1839).

Since the 1970s, a plethora of ecological studies has purported to examine the impacts of frequent fires on Sydney sandstone vegetation. However, the results of these studies have not been interpreted in the context of Aboriginal fire regimes and the historical, ecological consequences of their disruption including woody thickening and outbreaks of pests, parasites, diseases, and megafires (e.g., Mitchell 1848; Howitt 1891; Jurskis 2002, 2009, 2011*a*, *b*; Jurskis *et al.* 2003, 2011). Furthermore, these studies examined wildfire regimes or mixed fire regimes dominated by intense wildfires, whilst the abundance and richness of species have been measured at a fine scale so the conclusions have little relevance to consideration of the effects of frequent, mild, and patchy burning (e.g., Penman *et al*. 2007) on the natural (pre-European) composition and structure of the vegetation across the landscape (Jurskis *et al*. 2003, Bradstock *et al*. 1997, Jurskis 2011*b*).

The theory of extinctions of plant species (loss of biodiversity) as a result of frequent fire (e.g., Benson 1985 , Keith 1996, Keith *et al*. 2002) relies on the untenable assumption that the current vegetation in national parks represents the natural (pre-European) condition. It also relies on the unlikely assumption that frequent prescribed burns are sufficiently hot and uniform to kill or substantially damage most plants irrespective of life form or growth stage but not sufficiently hot and uniform to stimulate their reproduction or establishment (Jurskis *et al*. 2003, Jurskis 2011*b*). Another implicit assumption is that direct impacts of fire are the major influence on plant demography. Competitive interactions between species have been neglected (Bradstock *et al*. 1997). This is particularly apparent in the case of grasstrees on Sydney's sandstones, which are declining as a result of damage by high intensity fires, competition from thickening woody vegetation, and a disease that is favoured by infrequent, high intensity fires (that is, by modern fire regimes) (e.g., Tozer and Bradstock 2002, Jurskis 2005, Regan *et al*. 2011, Tozer and Keith 2012).

Tozer and Keith (2012) recognized that a focus on minimum allowable intervals between fires would not ensure the persistence of grasstrees, but they suggested that further studies are required to establish what patterns of shrub densities will promote the coexistence of contrasting species. However, there is no need for further studies because the landscape pattern established by thousands of years of frequent burning by Aborigines allowed grasstrees and shrubs to coexist. Shrubs occurred in much lower densities on most sites.

Fire suppression can promote *Phytophthora* root-rot by increasing topsoil moisture levels and changing soil chemistry, with adverse impacts on roots and direct benefits to the pathogen (Jurskis 2005). Increasing fuel loads promote high intensity fires that can raise water tables by interrupting transpiration and further benefit the pathogen (e.g., Fagg *et al*. 1986, Davison 1997, Jurskis 2005). Thus the inoculum level and extent of the *Phytophthora* has probably increased compared to natural levels (e.g., Pratt and Heather 1973, Jurskis 2005). It is likely that the health of grasstrees on Sydney's sandstone is generally reduced and that current mortality rates used in modeling by Regan *et al.* (2011) are unnaturally high. There is strong evidence that *Phytophthora* is indigenous to eastern Australia and that natural vegetation patterns reflected genetic susceptibility of plants as well as suitable soil conditions for the pathogen (Pratt and Heather 1973, Jurskis 2005). The history of grasstrees at Sydney strongly suggests that modern fire regimes disrupted these natural patterns.

The ecological studies have shown that interactions between fire regime and interspecific competition are important (e.g., Bradstock *et al.*1997) because absence of fire favours larger plant species over smaller species (Clark and McLoughlin 1986, Cary and Morrison 1995, Morrison *et al*. 1995, Morrison *et al*. 1996, Conroy 1996, Bradstock *et al*. 1997, Tozer and Bradstock 2002, Tozer and Keith 2012) and other fire studies in dry eucalypt forests have confirmed that many small groundcover plants decline rapidly after fire as larger shrubs develop (Jurskis 2011*b*). Thus biodiversity is likely to decline with less frequent fire because many smaller species are shaded out by fewer larger species and spatial heterogeneity due to site factors (e.g., Siddiqi *et al*. 1976, Bradstock *et al*. 1997, Keith *et al*. 2002) is obliterated (e.g., Siddiqi *et al*. 1976, Clark and McLoughlin 1986, Conroy 1996, Jurskis *et al*. 2003, Jurskis 2011*b*). Fire regimes also mediate intraspecific competition. Frequent mild fire regimes favoured mature plants over juveniles irrespective of species, whilst a regime of fire suppression can have the reverse effect, causing loss of mature trees and shrubs, and initiating changes in species composition (Jurskis 2009, 2011*a*).

Some proponents of the theory that prescribed burning threatens biodiversity have used a circular argument around species that are long lived obligate seeders (e.g., Benson and Redpath 1997, Enright *et al*. 2005). They claim that persistence of these species in the landscape is evidence that Aborigines did not burn frequently because burning at shorter intervals than their maturation period would eliminate them. Clark and McLoughlin (1986) recognized the historical evidence for frequent burning by Aborigines, but used the same circular argument to overestimate intervals between Aboriginal burning at seven to fifteen years. The persistence of the slow maturing obligate seeders on Sydney sandstone and of naturally rare plants (e.g., Keith *et al*. 2002) despite thousands of years of frequent Aboriginal burning provides clear evidence that both the theory and the circular argument should be discarded. It is apparent that slow maturing obligate seeders, once mature, are very tolerant of frequent mild fires (e.g., Jurskis 2009, 2011*a*) and that fire sensitive obligate seeders mature rapidly (e.g., Knox and Morrison 2005). Aboriginal burning over thousands of years undoubtedly selected genotypes attuned to frequent low intensity fire. Genotypes that were not so attuned, that is fire sensitive species, persisted in limited areas that were physically inaccessible to mild fires. A small number of plants on Sydney's sandstones are associated with wetter soils or dense shrub cover (Tozer and Bradstock 2002). Disruption of natural fire regimes has allowed these fire sensitive species to escape their refuges and interfere with fire management across the landscape (Clark and McLoughlin 1986, Conroy 1996, Jurskis *et al*. 2003).

The results of recent ecological studies are entirely consistent with the recorded history of Sydney's sandstone vegetation, but the way that these results have been interpreted to influence fire management is not, because the historical context has not been appreciated. For example, Morrison *et al*. (1996) claimed that there is "a clear conflict in south-eastern Australia between fire management practices based solely on prescribed burning for hazard reduction and the fire management practices necessary to maintain ecosystem biodiversity". However, this proposal fails to recognize that the current high fuel accumulation rates and extreme fire behavior during severe weather are products of changed vegetation structure and composition consequent to less frequent and more intense fire regimes. For example, Cary and Morrison (1995) studied sites where the understorey had been completely destroyed across at least five hectares by severe fires. Their finding that short intervals between these fires reduced species richness has no relevance to low intensity prescribed burning. Post-European fire management in national parks around Sydney has initiated a vicious circle that threatens biodiversity and human socioeconomy. The historical evidence indicates that Aboriginal burning favoured biodiversity over biomass and that there is no conflict between the socioeconomic and environmental objectives of low intensity prescribed burning.

Keith *et al*. (2002) acknowledged that the current Australian biota persisted through Aboriginal fire regimes for tens of thousands of years, but argued against reinstating those regimes because:

- they are difficult to specify precisely;
- they may have different consequences today because of habitat fragmentation and introduction of exotic biota;
- they were implemented to provide food whereas conservation has "*very different goals*" such as protecting rare plants, which may have had no value to Aboriginal people and may have been disadvantaged by their burning;
- they may be too expensive to apply across the landscape because of their fine scale.

However, the concept that frequent mild fire regimes would need to be defined precisely before they could be successfully implemented is not valid. These fires are inherently patchy (e.g., Penman *et al.* 2007) and fire behavior varies with site factors at a fine scale (e.g., Bradstock *et al.* 1997). Habitat fragmentation is irrelevant to the discussion for the same reasons. Invasion by exotic biota can be minimized under natural fire regimes (e.g., Jurskis 2012). Exotic plant invasions on Sydney's sandstones depend on unnatural nutrient enrichment (Lake and Leishman 2004), whereas frequent burning at intervals around five years can maintain stable nutrient cycles on such low nutrient sites (Turner *et al*. 2008).

There is no doubt that Aboriginal burning was economically and culturally motivated (e.g., Pyne 1998, Gammage 2011) and it is clear that the best way to conserve ecosystems shaped by about forty thousand years of Aboriginal burning would be to continue in a similar vein. Infrequent burning obliterates fine scale environmental variation (e.g., Clark and McLoughlin 1986, Conroy 1996), whereas frequent mild burning enhances it and facilitates low input and low cost management (Jurskis *et al*. 2003).

Kenny *et al*. (2004) reviewed the fire ecology of Sydney sandstone vegetation and concluded that the "domain of acceptable fire intervals" was 7 yr to 30 yr and that some intervals greater than 20 yr were "desirable." Clearly, the guideline is intended to maintain the status quo, and this will perpetuate the accumulation of woody vegetation, dangerous fuel loads, and pathogenic inoculum at the expense of understory diversity and healthy soil conditions. The guideline is apparently based on a philosophy of minimizing human "interference" rather than on any historical or ecological foundation.

CONCLUSIONS

Contrary to the views of many modern fire ecologists, human ignitions were the dominant cause of fire in most Australian ecosystems for thousands of years (Pyne 1998; Kershaw *et al*. 2002; Gammage 2011; Jurskis 2011*a*, *b*). Patchy Aboriginal burning undoubtedly limited recruitment of woody plants by killing seedlings on sandstone around Sydney as it did elsewhere (Mitchell 1848, Howitt 1891, Noble 1997, Jurskis 2009). Frequent, mild, and patchy fires in sparsely shrubbed vegetation leave many established woody plants unscathed (e.g., Jurskis *et al.* 2003, Penman *et al*. 2008). Thus, recruitment after such fires is not a conservation issue as has often been suggested.

Studies of prescribed burning have confirmed that most obligate seeders are favored by frequent mild fire whilst a few common large shrubs are disadvantaged (Jurskis *et al*. 2003; Penman *et al*. 2008, 2009; Jurskis 2011*b*). In the absence of frequent burning, these few shrubs have commenced to shade out many smaller and less common species within three or four years, reducing diversity (Penman *et al*. 2008, 2009; Jurskis 2011*b*).

Other studies of fuel accumulation (Birk and Bridges 1989), fire risk (Boer *et al*. 2009) nutrient cycling, and tree health (Turner *et al*. 2008) in dry eucalypt systems have shown that burning at three to six year intervals can maintain dynamic stability and ecological resilience in these systems (Jurskis 2011*b*). Physical records (e.g., Singh *et al*. 1981, Burrows *et al*. 1995, Ward *et al*. 2001, Hassell and Dodson 2003, Mooney *et al*. 2011: Figure 2) and historical records (Mitchell 1848, Curr 1883, Howitt 1891, Abbott 2003, Gammage 2011) support these studies of ecological processes pointing to ecosystems shaped by extensive, frequent Aboriginal burning.

Australia is fortunate in having good historical records of Aboriginal fire regimes and vegetation before they were impacted by European settlement (e.g., Pyne 1998, Gammage 2011). These show that prehistoric physical evidence cannot provide a reliable record of mild fire regimes. Even though historical records may be scant, such records should guide interpretation of physical evidence as well as interpretation of ecological studies.

Human fires can support biodiversity by restoring and maintaining natural, open conditions that favour ancient trees, small understorey plants, and bare ground as well as the rare species that depend on them (Jurskis 2009, 2011*a*, *b*). In eastern Australia, these include Hastings River mouse (*Pseudomys oralis*) (Tasker and Dickman 2004), the orchid *Prasophyllum correctum* (Coates *et al*. 2006), superb parrot (*Polytelis swainsonii*) (Manning *et al*. 2006), eastern brown treecreeper (*Climacteris picumnis victoriae*) (Ford *et al*. 2009), and broad-headed snake (Pringle *et al*. 2009). Informed application of human fires could also reverse declines in common species such as grasstrees.

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