HOTSPOTS FIRE PROJECT

Fire and Grazing in the Northern Rivers Region

Draft 1, Preliminary Draft for Comment

Dr Penny Watson

Project Ecologist

April 2006

Nature Conservation Council of NSW
The voice for the environment since 1955

Environmental TRUST

This project has been assisted by the New South Wales Government through its Environmental Trust.

Fire and Grazing in the Northern Rivers Region

Draft 1: Preliminary Draft for Comment

Dr Penny Watson

Project Ecologist

April 2006

This document has been prepared to help Hotspots and local NRM staff provide accurate information to graziers in the Northern Rivers region on the effects of fire and grazing regimes. It draws mostly on an extensive literature review. Comments, particularly from those with on-ground experience, are very welcome. Please contact Penny on (02) 9477-7361, or at pennyw@efa.com.au before 31 July 2006.

Table of Contents

1. Background

1.1 Introduction

Over recent years, both livestock producers and scientists have changed the way they view grazed landscapes. Where once a pasture was seen as a crop for grazing animals to harvest, more recently grazed grasslands, woodlands and forests have come to be regarded as complex functioning ecosystems of plants and animals (Whalley 2000). Managing grazed landscapes for ecosystem sustainability is increasingly considered an important goal (Simpson 2000). And while animal production is of course the primary focus for most graziers, opportunities to enhance native biodiversity within grazing enterprises are also increasingly being advocated (Kirkpatrick and and Gilfedder 1999, McIntyre *et al.* 2001, 2002a,b; Nadolny *et al.* 2003).

In the Northern Rivers region of NSW fire plays a part in both grazing management and biodiversity conservation. This document explores the role of fire in grazed native vegetation, and investigates whether fire regimes compatible with both these management aims can be identified.

Research literature addressing the effect of combinations of fire and grazing regimes is sparse, as is that which considers both pastoral purposes and biodiversity conservation aims. This review therefore draws on findings from a wide range of studies of the effects of each disturbance, as well as on ecological theory and on literature addressing best practice management of grassy vegetation.

The document begins with notes on the focus of the review (unimproved grassy landscapes) and on grazing industry practices in the Northern Rivers region (Sections 1.2 to 1.4). Before considering the role of fire, the effects of grazing itself on biodiversity and pasture condition (Section 2.1), and on fuel loads (Section 2.2), are explored. Also by way of background, Section 3 investigates the effects of fire on soil and nutrient processes.

In Section 4 a variety of aims of on-farm burning are considered. These aims include:

- To covert rank grass to palatable ‘green pick’
- To attract animals to particular areas
- To maximise grass production
- To encourage particular ground layer species
- To manage shrub and tree abundance
- To prevent wildfire burning out large areas, and
- To encourage native plant and animal species.[1]

Questions explored in relation to these aims include: does the evidence suggest that fire is really useful for this purpose? Might particular fire regimes be more useful than others in achieving this aim? Might the interaction between grazing regimes and fire regimes be important?

Management implications are then discussed and areas for further research suggested (Section 5).

---

[1] The role of fire in conservation of native plant and animal species in grassy vegetation of the Northern Rivers region is only summarised briefly in this review, as it is dealt with in detail in another Hotspots document (Watson 2006).

1.2 Grazing and conservation in the Northern Rivers

The Northern Rivers region in northeast NSW covers a diverse geographic area from the coast to the eastern slopes and plateaus of the Great Dividing Range. Agriculture is the primary land use over much of the inland parts of the region, while forestry and national parks also occupy extensive areas. Beef cattle contribute more than any other commodity to the value of agricultural production in the Northern Rivers; dairying is also important though to a decreasing extent (DTRS 2005, BRS nd). According to the Commonwealth Bureau of Rural Science (BRS nd) most cattle grazing takes place in "native grasslands and minimally modified pastures," some occurs in native forests and woodlands, while a small proportion takes place in "highly modified pastures." Much of the industry, then, is conducted in native vegetation. "Grazing natural vegetation" is credited as the primary source of revenue for the region's grazing industry (BRS nd).

Grazing enterprises generally occur in grassy vegetation found on relatively fertile soils, as the infertile soils which support shrubby sclerophyll woodlands, forests and heaths are unlikely to provide sufficient economic return.

Within these grassy landscapes, native vegetation is often found on hillsides and ridges. On fertile ground such as foot slopes and valley floors, pastures are frequently improved through sowing of introduced species and use of fertiliser (Jarman *et al.* 1987). Trees in these areas are often limited to shelter belts. However on less fertile hillsides, native grasses and herbs are often retained in a woodland matrix for rough grazing. This pattern occurs both locally (Tac Campbell, pers. comm. 2005), and in other parts of south-eastern Australia (Johnston 2000, Simpson 2000). It is in these areas that conservation of biodiversity and cattle grazing are most likely to be compatible.

The focus in this document is therefore on grassy landscapes which have not been sown to exotic pasture or modified through fertiliser application. Although issues relevant to the Northern Tablelands are canvassed, the need for this review arose from Hotspots' work with graziers in lower-altitude areas below the escarpment, where the association between grazing and fire is both longstanding and current. I have therefore looked firstly for information relevant to this environment.

1.3 Grazing regimes in the Northern Rivers

Although the notion of cell or crash grazing, where cattle are rotated through a series of paddocks, is gaining popularity on the Northern Tablelands (Earl and Jones 1996, Reseigh *et al.* 2003), it appears that most grazing below the escarpment is continuous (Jim Morrison pers. comm. 2005). Base stocking rates are determined by the carrying capacity of the country in spring (Tac Campbell, pers. comm. 2005), as the driest months in this region occur in winter and early spring (Bureau of Meteorology 2005).

Grazing in the Northern Rivers region takes place not only on private property, but also in State Forests. Grazing leases are more common in dry forests than in wetter areas (York 1997; Doug Binns, Forests NSW, pers. comm. 2005). On the Northern Tablelands, cattle are generally put on to State Forest leases for approximately six months over the cooler half of the year, to spell adjacent pastures (Tasker and Dickman 2004). Stocking rates in State Forests are low relative to those on private property (York 1997, Tasker and Dickman 2004).

In both State Forests and on private property, some areas will be more easily accessible to cattle than others. Watering points will affect where cattle choose to graze (Henderson and Keith 2002). Grazing pressure in native pastures is therefore likely to vary across the landscape.

1.4 Fire regimes in the Northern Rivers

What fire regimes are employed by graziers in the Northern Rivers region?

Only one study documenting the use of fire by Northern Rivers landholders in recent decades was located, and its coverage is limited in both time and space. Informal assessments of fire frequency differ. Concern that grazing-related burning may be too frequent, both along the northern NSW coast and in adjacent Tablelands forests, is quite often expressed. This concern has formed part of the rationale for a number of research studies in recent years, including those of York (1997, 1998, 1999b), Kitchen (2001), Henderson and Keith (2002) and Tasker (2002). That annual burning for ‘green pick’ was widespread from early in European settlement in both northern NSW and southern Queensland is attested by a number of sources (Shaw 1957, Tothill 1992, Stubbs 2001).

Jarman *et al.* (1987) mapped fires on grazing properties along Wallaby Creek in the upper Clarence River Valley over two years in the early 1980s. Fires were patchy, rarely overlapped, and their total area covered less than half the landscape. The authors estimated the average interfire interval at any one point in the landscape would be approximately four years. Although landholders aimed to set fires in August or September, this was not always possible due to weather, and observed fires spanned the months from June to January (Jarman *et al.* 1987, Southwell and Jarman 1987).

Grafton-based agronomist Tac Campbell (pers. comm. 2005) reports that the amount of burning undertaken varies from farm to farm: some graziers burn often, others less so. Tac considers that burn frequency at any particular point in the landscape is probably lower than many believe: people see smoke, Tac believes, and draw conclusions that are not necessarily correct. He estimates that point frequency varies from 3 to10 years, where burning occurs. This estimate is similar to the burn frequency suggested by Don Johnson, a grazier from the Bonalbo district: Don recommends burning at 3 to 5 year intervals in open grassy country, and between 5 and 10 years in forest (Johnson 2005). Tasker (2002) sought detailed information on fire regimes from lease-holders in Tablelands wet sclerophyll forests; she concluded that most leases were burnt at variable intervals between 1 and 5 years, usually in Spring (Tasker and Dickman 2004), although the occasional landholder aimed to burn every year (Tasker and Bradstock, submitted).

Indirect evidence that grazing-related fire may not be as frequent as some people fear comes from a survey in forests south of Casino. Mean litter depth was similar in grazed and ungrazed sites, averaging around around 1.8cm (York 1998). Although 1.8cm does not represent a deep litter layer, neither is it indicative of very recent burning. These findings therefore suggest that even in grazed areas, at least a couple of years had passed since the last fire.

In Tac Campbell’s experience, although grazing-related burning is widespread in the Northern Rivers, a lot of country is also managed to exclude fire. Tac believes that burning is becoming less frequent. Low rainfall over recent years may be one reason why graziers are limiting their use of fire: landholders concerned that spring rains may not evenuate are retaining their grass, as rank feed is better than no feed at all (Jim Morrison pers. comm. 2005).

Tablelands ecologist Chris Nadolny (pers. comm. 2006) reports that although many graziers use fire in the gorges and on the eastern edge of the Northern Tablelands plateau, very little fire is used in the central Tablelands.

2 Grazing effects

2.1 Grazing, biodiversity and pasture condition

Before exploring the effects of fire on pastures, it is useful to consider how grazing itself affects biodiversity and pasture condition.

Grazing is a pervasive disturbance in grassy forests and woodlands. In eastern Australia prior to European settlement, forests were grazed by macropods, wombats and other native animals, as well as by invertebrates. Pastoralists moved domestic stock into grassy forests and woodlands in the early decades of settlement, which in Northern NSW occurred in the 1840s (Stubbs 2001). Many forests and woodlands would have been grazed almost continually by livestock since then.

Although in some parts of the world domestic stock were similar to the animals which grazed the countryside prior to settlement (eg bison in North America), in Australia they differed considerably. Domestic stock grazing is thus less likely to mimic the impacts of grazing by native animals here than elsewhere, and thus may be less compatible with retention of native plants and animals (Lunt 2005).

Grazing opens up the grass canopy and influences species composition through selective defoliation, trampling and increased access to light. Species vary in their responses to these perturbations (Tremont 1994). Even within a species, responses may differ in different environments and circumstances (McIntyre and Martin 2001, Vesk and Westoby 2001). The following discussion focuses on studies from eastern Australia. Effects of grazing on trees, shrubs and herbaceous species are considered in turn.

Similarities and differences between fire and grazing as agents of disturbance in native ecosystems are discussed in Section 4.7.2.

2.1.1 Grazing and trees

No studies of the effects of grazing on trees in the Northern Rivers region were located [though some may be on their way]. However it is generally believed that stock grazing limits tree regeneration (Sivertsen 1993, Cluff and Semple 1994), and most, but not all, field studies read for this review support that belief. Both seedling establishment and transition from suppressed lignotuberous seedling[2] to sapling and adult may be affected. In grassy remnant woodlands in the Riverina Spooner *et al.* (2002) found significantly more eucalypt recruitment in remnants which had been fenced to exclude livestock than in nearby unfenced areas. Landsberg *et al.* (1990) reported low levels of eucalypt regeneration in wooded pasture sites on the Southern Tablelands (grazing was mostly by sheep), and this was reflected in significant differences in average per tree basal area when these sites were compared to paired control sites which had experienced little or no grazing over the past 10 years. And in *Eucalyptus maculata* forest near Maryborough in south-east Queensland, cattle grazing an experimental site were very effective at keeping suppressed eucalyts and resprouting black wattle from developing into saplings and adult trees (Tothill 1971). However Wellington and Noble (1985) found mortality of mallee eucalypt seedlings was not significantly reduced

[2] Seedlings of most eucalypt species quickly develop lignotubers, woody storage organs at the base of their stems which can produce shoots. These 'seedlings' may not grow into adult trees straight away, often persisting as low-growing plants in the understorey for many years.

when grazing by rabbits, kangaroos, sheep or invertebrates was excluded in north-west Victoria.

Livestock grazing can also affect adult trees. Landsberg *et al.* (1990) assessed the health of trees in remnants on the Southern Tablelands. Trees in pasture sites were "consistently and significantly" less healthy than those in paired control sites which had experienced little grazing, and there were significantly more dead trees in pasture sites. The aim of this study was to assess various theories as to the causes of rural dieback. The authors concluded that nutrient enrichment of soils, particularly greatly increased nitrate levels, were translating into higher nutrient levels in eucalyptus leaves, which encouraged leaf-eating insects: there were many more insects in pasture stands and they grew faster and bigger than their counterparts in the ungrazed remnants. Elevated nutrient levels were probably due to redistribution by livestock (mostly sheep), who often camped under the trees in the pasture woodlands.

No studies of the differential effects of continuous versus crash grazing on trees were found.

2.1.2 Grazing and shrubs

A number of studies suggest shrubs can be disadvantaged by grazing, although this effect is not always particularly strong in local studies and may vary with soil type and region. Northern Rivers studies are summarised first:

- York (1997, 1998, 1999b) investigated the impact of grazing in State Forests in the Northern Rivers region. Areas with cow pats were compared with areas without, on three geologies: sandstone, mixed sediments, and unconsolidated sediments. Although this study found little difference between grazed and ungrazed sites for many groups of plants and animals, overall shrub species richness was significantly reduced in grazed areas. This effect was particularly pronounced on sandstone, which hosted more shrubby vegetation than the other two geologies. On mixed sediments, which were associated with Spotted Gum forest, differences in shrub species richness were slight, averaging 2.9 species per 0.1ha in grazed sites, and 3.1 in ungrazed areas. Cover of small shrubs (20-50cm) was significantly lower in grazed areas. There was also less cover of mid-sized shrubs (50-100cm) although this difference was not significant. Cover of shrubs over 1m tall was not affected by grazing.
- In an experimental study in the New England region, Clarke (2002) found seedlings of some shrub species were impacted by grazing, while others were not. Sheep appeared to have a greater impact than cattle or native herbivores.
- Clarke (2003) also investigated factors associated with disturbance across multiple sites on the New England Tablelands. He found a decline in shrub species richness and abundance in areas grazed by sheep and/or cattle, although this effect was less pronounced in woodland than where trees had been removed. Where trees had not been thinned, there were more shrub species where grazing had been intermittent than where it was continuous.
- Similar work in relatively wet grassy forests in Guy Fawkes River National Park found a somewhat lower species richness, and a much decreased density, of shrubs in sites which had more signs of cattle grazing, although the frequent burning that accompanies pastoralism in the area might also have played a role (Henderson and Keith 2002).

- In the Southern Highlands, Leigh and Holgate (1979) found increased mortality of some shrub species in plots grazed by native mammals in dry sclerophyll forest; post-fire seedlings were particularly affected.
- Also on the Southern Tablelands, Landsberg *et al.* (1990) found many fewer species of native shrubs in remnants used for stock grazing (mainly by sheep) than in paired remnants that had a history of light or no grazing.
- On the other hand, a study by Hill and French (2004) in Western Sydney's grassy woodlands found no effect of kangaroo grazing, and no interaction of grazing with fire on either shrub species richness or shrub abundance.

In some places grazing has been implicated in an *increase* in shrub density:

- Bennett (1994) considers the gap creation resulting from increased grazing pressure to be the most likely cause of a massive expansion of *Leptospermum laevigatum* on the Yanakie Isthmus near Melbourne; kangaroos and rabbits are the main herbivores in this area.
- A reduction in grass cover as a result of grazing is considered a major factor in the generation of the 'woody weed' problem in semi-arid regions of NSW (Noble 1997), as it is in southern Africa (Bond 1997).
- Shrub density increased rapidly on grazed plots in subalpine country where sheep grazing reduced competition from herbaceous species (Wimbush and Costin 1979), and where unpalatable shrubs were avoided by cattle (Wahren *et al.* 1994).

Grazing can encourage shrub populations to expand in two ways. Firstly, grazing reduces competition from grasses (Madany and West 1983), and may create gaps in the grass canopy where shrub seedlings can establish. Secondly, grazing reduces fuel loads and thus fire frequency and intensity (Noble 1997), which in turn reduces impact on shrubs (Section 4.5.4).

Some shrub species may be more vulnerable to grazing than others, and this may partly explain the contradictory findings above, as the suite of available shrub species will vary with soil type, region, and locally. Shrubs vary in their palatability to stock, and this is likely to differentially affect mortality rates. Shrubs which are able to regenerate between fires rather than needing a fire to cue seed release or germination may be better able to take advantage of the gaps and reduced competition from grasses that grazing affords. Obligate seeder species which are not equipped to resprout after fire may be more vulnerable to grazing than resprouting species[3], as the latter regeneration strategy may also be effective after defoliation. Fast-growing and taller species will be more able to grow beyond the reach of livestock.

2.1.3 Grazing and herbs

The effect of grazing on herbs is of particular interest. Much of the plant diversity in grassy forests and woodlands is found in the herbaceous layer (York 1999b). And it is the grasses and forbs which provide most of the fodder for cattle, as well as for native grazing animals.

[3] Plant species recover after a fire in one of two main ways. Adults of resprouting species regrow from shoots after a fire; shoots may come from root suckers, rhizomes, or woody lignotubers at the base of the plant, or from epicormic buds on stems. Adults of obligate seeder species die when their leaves are all scorched in a fire, and rely on regeneration from seed (Gill 1981).

The effects of grazing on grasses and forbs[4] are complex, as they are for shrubs. Both positive and negative effects on species richness have been reported.

- York (1999b) found no differences in species richness of grasses, herbs, ferns or sedges between grazed and ungrazed sites in his study south of Casino.
- McIntyre *et al.* (1995) assessed the effects of grazing pressure on species in grassy woodlands on the New England Tablelands, by lifeform. Heavily grazed sites had fewer plants with erect rosettes, or persistent buds between 1 and 30 cm above ground. Clarke (2003) also identified a suite of Northern Tablelands species which was negatively impacted by heavy grazing, including ferns, geophytes and twiners. However many other herbaceous native species were tolerant of grazing, and native species dominated even heavily grazed sites. A third regional survey on the Tablelands near Armidale found higher native species richness in ungrazed and episodically grazed sites than in sites that were continuously grazed (Reseigh *et al.* 2003). Sites in all these studies covered a wide range of soil types. However species richness was consistently *higher* in grazed areas at a basalt Tablelands experimental site (Tremont 1994).
- Further north on the fertile basalt-derived soils of south-east Queensland's Darling Downs, native species richness was highest at moderate or high levels of grazing, although a small number of grazing-intolerant species could be identified (Fensham 1998). In less fertile soils of the Brisbane River catchment, McIntyre and Martin (2001) found no difference in species richness between heavily and lightly grazed patches on granite, however species richness was lower in heavily grazed patches on sandstone. McIntyre *et al.* (2003) also found species richness was highest at medium levels of grazing pressure in eucalypt woodlands in south-east Queensland.
- Prober and Thiele (1995) found grazing affected species richness and composition in the White Box (*E. albens*) woodlands of the Central Western Slopes of NSW, with some native species severely disadvantaged by even light grazing, and additional taxa reduced or eliminated where grazing pressure was heavy.

Some variation in the effects of grazing on herb diversity may relate to productivity, which depends on the availability of resources for plant growth. Productive areas – those with relatively fertile soils, high rainfall, and a long growing season – may be more prone to competitive exclusion of small herbaceous species in the absence of disturbance than less productive areas. Small herbs get shaded out by tussock grasses which can become very thick in the absence of grazing (or fire). An analysis of many studies of grazing impacts in high and low resource systems around the world found that species richness often increased with grazing intensity in high resource sites, but decreased where resources were low (Proulx and Mazumder 1998). This explanation also appears to fit the results of the studies reported above; the places where grazing was associated with increased species richness tend to be more productive, while a decrease in ground layer diversity has more often been found in less productive soils and/or in lower rainfall areas. Tremont's description of his ungrazed plots (on basalt) suggests that competition from dominant species might indeed be the key factor: large tussock grasses dominated, litter covered all bare ground, small statured plants were uncommon, forbs were sparse, and geophytes[5] were totally absent (Tremont 1994). Vesk and Westoby (2001) collated the results of 35 published studies of the effects of grazing pressure

[4] A forb is a herbaceous plant which is not a grass, sedge or rush.
[5] A geophyte is a forb with an underground storage organ, such as a bulb or tuber. Many native lilies and orchids are geophytes.

in Australian rangelands. Many species showed inconsistent results across studies. Species were more likely to decrease under grazing in low rainfall areas than where rainfall was high.

Lunt (2005)[6] points out additional factors that may affect the findings of studies on grazing impacts on ground layer diversity. These include the relative palatability of dominant and sub-dominant species, characteristics of grazing (eg type of animal, stocking intensity, continuity of grazing), and the spatial scale of disturbance regimes and studies. Grazing may increase ground layer species richness on a small scale, while simultaneously decreasing it at a larger scale by selectively depleting grazing-sensitive species (Landsberg *et al.* 2002).

2.1.4 Grazing and invertebrates

York's study in State Forests south of Casino (York 1997, 1998, 1999b) focussed primarily on invertebrates. No significant differences in richness, abundance, or species composition were identified for invertebrates overall, nor in any of 16 groups with sufficient numbers for testing (York and Tarnawski 2004). There was some indication that beetle species composition might shift with increased intensity of grazing, however neither beetle abundance nor beetle species richness was affected by grazing, in fact both were higher in grazed sites, though not significantly so. Harris *et al.* (2003) also failed to identify any significant differences between the two treatments in an in-depth analysis of the data for spiders.

Landsberg *et al.* (1990) found much higher abundances of insects on trees in their grazed remnants on the Southern Tablelands (grazing was mostly by sheep) than on matched control sites which had experienced little or no grazing. However this was not really good news, because insect defoliation was closely associated with rural dieback in these grazed remnants.

Grazing effects on biodiversity

Research indicates that grazing:

- Can reduce tree regeneration and may be associated with a decline in tree health.
- Can reduce shrub diversity and density, though in some places increased shrubbiness has been attributed to grazing.
- May reduce or enhance herb diversity. Some grazing in productive grassy forests and woodlands may help create space between grass tussocks for smaller plants.
- Does not appear to affect invertebrates in Northern Rivers forests.

[6] Although focused on temperate rather than sub-tropical grassy vegetation, this literature review provides an excellent in-depth, management-oriented discussion of the varied effects of grazing on biodiversity.

2.1.5 Grazing and native pasture condition

Detailed studies of Northern Rivers native pastures below the escarpment have yet to be conducted. More is known about pastures on the Northern Tablelands, the Western Slopes and in south-east Queensland.

Because grazing animals prefer some species to others, palatable species are always at risk of being 'grazed out' of pastures. Grazing also tends to disadvantage species whose growing points are exposed and accessible, while species with underground rhizomes or a ground-hugging habit are more protected (McIntyre *et al.* 1995).

At a landscape level, changes in species composition with grazing have been documented for native pastures on the Northern Tablelands and the Western Slopes. Tall tussock grasses such as *Themeda australis*[7], *Sorghum leiocladum* and *Poa sieberiana* which originally dominated have been replaced by species of *Bothriochloa*, *Aristida* and *Austrodanthonia* that are better able to persist under grazing (Prober and Thiele 1995, Chilcott *et al.* 1997, Prober *et al.* 2002a, Nadolny *et al.* 2003). Sites degraded through very heavy grazing, particularly if accompanied by nutrient enrichment, can be dominated by annual exotics (Prober *et al.* 2002b).

At a smaller scale, grazing pressure in a paddock is often patchy. CSIRO researchers have studied what happens to the patch structure of native pastures with different levels of grazing in south-east Queensland. Some grazing opened up the grass canopy of the large tussock species which dominated in the absence of grazing, making room for smaller perennial species to co-occur (McIntyre and Tongway 2005). With increased grazing pressure large tussock species were progressively displaced by smaller perennial species. Large-statured grasses that did remain as grazing pressure increased tended to be less preferred species such as *Aristida ramosa* and *Cymbopogon refractus*. Very heavily grazed patches took on the structure of a mowed lawn; these 'lawn' patches had less species per unit area, and often contained taxa with runners which grow along or just under the ground, like *Cynodon*, *Digitaria* and *Paspalidium* species (McIvor *et al.* 2005). Lawn patches had more exotic species than tussock patches (McIvor *et al.* 2005). Removal of grazing pressure in a mixed patch pasture saw the abundance of large tussock grasses, particularly *Themeda australis*, increase, as suppressed plants of these species grew and flowered (McIvor *et al.* 2005). This did not happen, however, when heavily grazed lawn patches were protected.

While lawn patches may play a useful role, along with other types of patches, in increasing the range of fodder species in a pasture, they may also have a down side, particularly where long-term sustainability of pastures is concerned. Patch characteristics are just starting to be studied in Australia. However in similar pastures in South Africa, Fuls (1992) found that overgrazed lawn patches had much less capacity to absorb water after a storm than patches of perennial tussock grasses, particularly *Themeda triandra* (synonym *T. australis*). Overgrazed patches were also prone to severe erosion. In south-east Queensland, McIntyre and Tongway (2005) found the basal area of large tussock species was associated with higher values on three indices of soil surface condition (stability, infiltration, nutrient cycling), although these measures were indirect and are yet to be validated.

The above findings have led CSIRO researchers to recommend landholders graze conservatively to maintain dominance of large and medium tussock grasses over 60-70% of native pastures (McIntyre *et al.* 2000, 2001, 2002a; McIntyre and Tongway 2005). These

[7] In some Australian states this grass species is called *Themeda triandra*, a name which recognises the close affiliation between the African and Australian forms of the species.

recommendations are designed with both production and conservation goals in mind. They are based on: "(i) a compromise between maximizing livestock production and leaving sufficient biomass to support critical soil and vegetation processes; (ii) providing areas of lenient grazing within pastures for the persistence of grazing-sensitive plants; and (iii) providing a range of grassland structures as habitat for grassland invertebrates, and ground-dwelling and feeding vertebrates" (McIntyre and Tongway 2005:48).

Grazing and pasture condition

- Tall native perennial tussock grasses tend to decrease with grazing, but may recover when paddocks are rested.
- Perennial tussock grasses probably play an important role in long-term pasture sustainability.
- CSIRO researchers recommend grazing conservatively to retain dominance of tussock grasses over 60-70% of native pastures.

2.2 Grazing and fuel reduction

An issue that sometimes arises when the topics of fire and grazing are discussed is the role of grazing in fuel reduction. Many landholders, including Forests NSW (State Forests of New South Wales 2002), use grazing to decrease the risk of destructive wildfire. But is this measure effective?

One reason the effectiveness of grazing as a fuel reduction measure is questioned is because of the findings of a study in mainland Australia's alpine and subalpine country. Here, high levels of sheep grazing created and maintained spaces between grass tussocks. This also allowed shrubs to increase in size, due to reduced competition from the grasses (Wimbush and Costin 1979). Thus in this environment, it is unlikely that 'grazing reduces blazing.'

It is also the case that even where fuels have been reduced, there is no guarantee that fires under severe weather conditions will not burn through low fuel areas (Bradstock *et al.* 1998). Fuel reduction measures of all kinds are only designed to reduce the *risk* of damage from wildfire; no amount of fuel reduction will ever reduce risk to zero. On the other hand, there is considerable evidence, as well as logical argument, to support the contention that lower fuel loads are associated with reduced fire intensity and thus with greater potential for fire control (Section 4.6.1; Stinson and Wright 1969 summarised in Whelan 1995:31).

In grassy eastern Australian ecosystems where shrub density is low, there is evidence that grazing reduces grass biomass (Walker *et al.* 1986b in *Eucalyptus crebra* woodland in south-east Queensland; Orr *et al.* 1997 in spear grass pastures in Queensland), and that biomass increases when grazing is removed (Chilcott *et al.* 1997 on the New England Tablelands). In a Victorian subcoastal woodland, Robertson (1985) found that less litter accumulated in grazed areas than where grazing was excluded. In forests south of Casino, York (1998) found that the cover of herbs and small shrubs up to 50 cm in height was lower and more spatially variable in grazed areas.

In woodlands and forests, while grasses make up a proportion of the fuel load, most of the fuel that accumulates over time comes from trees: it consists of leaves, bark and twigs in various stages of decomposition (Simmons and Adams 1999, Williams *et al.* 2002, Watson 2005). So while removal of grass biomass may help reduce fuel loads, it will not stop fuel accumulating altogether.

Noble (2004)[8] has carefully considered the potential of grazing, by both native and domestic herbivores, for reducing fuel load in grassy vegetation in the ACT. His review explicitly considers issues of biodiversity conservation and pasture condition. He concludes that although the severe fire weather in the ACT during the 2003 fires would probably have overridden fuel reduction benefits, under more moderate conditions "the probability of successful suppression of any unplanned fire burning in grassy woodlands would be considerably enhanced if herbaceous fuels had been significantly reduced by prior grazing" (Noble 2004:26). Noble (2004) recommends conservative stocking, together with adjustment of stocking rate in response to fluctuations in forage availability, to balance maintaining appropriately low fuel levels with environmental considerations.

[8] This detailed document is available through the internet, and is recommended as a good starting-point for those wanting to explore this issue further.

3 Fire effects on soil and nutrient processes

3.1 Soil health and burning

Before considering the effectiveness of fire in meeting specific goals on grazing properties, it may also be useful to outline what we know about the effects of repeated burning on soils.

Obviously, farmers are concerned to maintain, and if possible enhance, the long-term capacity of soils to support vegetation which will in turn support production activities. The question of whether burning compromises soil health and leads to pasture degradation over the long term is therefore important.

What factors are associated with soil health? According to Whalley (2000) deep soil roots, healthy populations of ground-dwelling invertebrates and litter cover are all associated with healthy soils. Permeability across the soil-air boundary allows water to infiltrate deep into the soil where it can nourish plant growth, rather than running off and causing erosion. Agronomists generally recommend retention of litter in pastures as a way to maximise soil moisture and nutrients, and thus encourage grass and herb growth (Tac Campbell, pers. comm. 2005).

In this section the effects of fire on soil organic matter particularly roots, soil nutrients particularly nitrogen, soil microfauna, erosion and water infiltration, are explored.

Sorting out the effects of fire on soils is not easy. Factors to remember when considering the research on fire and soils include:

- The effects of a single fire on soil parameters are not necessarily the same as the effects of a series of burns.
- Effects are likely to differ with soil type (Walker *et al.* 1986a, Aranibar *et al.* 2003).
- Effects are likely to differ with differing fire regimes (ie with the frequency, intensity and season of fires).
- Studies which focus on the long-term effects of a series of fires are relatively rare, as these studies are logistically difficult and expensive (Andersen *et al.* 1998, Edwards *et al.* 2003).
- Long-term studies which do exist are limited in the duration of their treatments. The longest have been going for about 50 years.
- The number of treatments assessed in any long-term study is necessarily limited. Often analysis focuses on the effects of annual burning versus fire exclusion. These are both extreme regimes, and thus may be of limited value in determining the appropriateness of a range of more moderate fire return intervals.
- Studies which consider the additional effects of grazing regimes on soils subject to different fire frequencies are virtually non-existent.
- Local studies addressing the effects of fire on soils have yet to be conducted. This review therefore draws on research from outside the Northern Rivers region, and indeed from outside Australia.
- The effect of fire regimes on soil properties may be influenced by the composition of the vegetation that develops in response to those regimes, as much or more than by the effects of the fires themselves (Aranibar *et al.* 2003). Feedback loops between vegetation and soils may be involved.

The complexity of the topic and the limitations of the research base mean that clear generalisations about the long-term effects of periodic burning on soils are not readily available. After a comprehensive review Walker *et al.* (1986a:209) concluded that:

> "Fire affects many ecosystem processes, and consequently the effects of fire on the soil system, on plant growth and on the long-term stability of an ecosystem are complex and open to diverse interpretations. …. only limited information is available on the longer-term impact of fire in most Australian ecosystems where fire is widely used for management purposes."

This conclusion is probably still valid today. However despite these limitations, some information on fire and soils is available. I have concentrated on studies in grassy ecosystems. While it is likely that similar findings from a range of environments is indicative of fairly universal processes, without local studies it is impossible to know for certain that conclusions will be valid for Northern Rivers landscapes. For this reason and because of the limitations described above, conclusions in this part of the review should be considered tentative.

3.2 Soil organic matter

Organic matter in the soil comes from leaf litter, plant roots, and other living and dead organisms in various stages of decay. It influences both the physical and chemical properties of soil in multiple and complex ways. Temperature and rainfall affect the amount of organic matter in the soil: in general there is more organic matter in soils where it is cooler and/or wetter. Sandy soils tend to have less organic matter than clay soils. Soil organic matter is normally measured as organic carbon (C) (DPI 2002, McKenzie *et al.* 2004).

High levels of soil organic matter are generally regarded very positively. For example the NSW Department of Primary Industries considers that "Organic matter is the lifeblood of fertile, productive soil" (DPI 2002). Benefits of organic matter include improved soil structure, improved drainage, better moisture retention and regulation of nutrients (DPI 2002).

Burning removes litter on the surface of the soil, and thus removes the potential for this material to be incorporated below ground. It may therefore seem obvious that regular burning would be associated with lower levels of soil organic matter. However studies of long-term effects of a series of burns find that this is not always the case. In some situations soils from regularly burnt areas show higher levels of soil organic matter than unburnt areas, while in others the reverse has been found. Frequent burning appears to encourage grasses to develop larger root systems, and this may be an important part of the dynamics of fire in pastures.

Two studies, one from South Africa (Fynn *et al.* 2003) and one on the tallgrass prairies of Kansas in the United States (Ojima *et al.* 1994) are of particular interest because they both assessed burning treatments which had been implemented over many years, and because their design included replication.

Fynn *et al.* (2003) used data from a 52 year experiment in South African savanna country located at approximately the same latitude as northern NSW. As on the NSW North Coast, rain falls predominantly in summer, winters are mild, and *Themeda triandra* (a synonym for *Themeda australis*) is one of several dominant tussock grasses. Dynamics are thus likely to be similar in the two environments. This study included fires at 1, 2 and 3 year intervals, and in different seasons, as well a fire-exclusion treatment. The results for organic carbon differed with soil depth. In the top 2 cm, some burning regimes were associated with a reduction in organic carbon, while others were not. Reductions were associated with frequent burning in autumn and winter. Between 6 and 10 cm, however, organic carbon content was greater in burnt plots, although not significantly so. Fynn *et al.* (2003) attribute this finding to greater turnover of root material in burnt treatments, as organic matter at depth tends to come from roots rather than from surface litter. Annually burnt plots had a much greater root biomass in the 4-10cm layer than unburnt plots. On the other hand, there was considerably more surface litter in unburnt than in annually burnt plots, providing a source of organic matter for upper soil layers (litter levels in other burning treatments were not measured). The authors attribute the relatively high levels of organic matter in the top 2cm of the soil in the spring-burnt treatments, even under annual or biannual burning, to the fact that this regime allowed litter from the previous growing season to decompose over winter.

Ojima *et al.* (1994) compared plots burnt annually in spring for over 50 years with plots unburnt during this time. Again this is a summer rainfall area, though cooler and slightly drier (annual rainfall averages 835mm) than the North Coast. Findings were very similar to those from South Africa, with lower levels of soil organic carbon in the top 5 cm of the burnt plot soils, but higher levels between 5 and 15 cm. There was almost double the level of carbon per unit area in dead and live roots in burnt relative to unburnt plots. As in South Africa, burning appears to have encouraged root growth. A second tallgrass prairie study (Johnson and Matchett 2001) has since confirmed that this is the case.

Fire and soil organic matter (SOM)

- Research suggests that regular burning may decrease SOM in upper soil layers, but increase it further down the soil profile through encouraging root growth.
- Fire regimes which allow opportunities for litter to break down to at least some degree are likely to benefit SOM levels in upper soil layers.
- A precautionary approach to maintaining SOM under regular burning might involve:
    - Burning at 2-5 year intervals rather than annually,
    - Burning in spring rather than autumn.

A similar though less comprehensive and unreplicated fire frequency experiment in dry sclerophyll forest near Bauple in south-east Queensland found no significant difference in organic carbon between treatments (Guinto *et al.* 2001). In terms of trends, organic carbon levels in the top 20cm were highest where burns had taken place every 2-3 years, next highest in unburnt plots, and lowest where burns had occurred annually. In a companion experiment in wet sclerophyll sites, however, organic carbon levels, which were high relative to those in the dry forest, were lower in burnt than in unburnt forest, and declined with burning frequency. A second South African study also failed to detect a difference in soil organic carbon between annual, triennial and long-unburnt treatments, in the top 5cm of soil (Aranibar *et al.* 2003). The highest levels in this study were found in clay soils burnt every three years.

The above findings suggest that a precautionary approach to maintaining soil organic carbon levels under regular burning might involve spring rather than autumn fires, at intervals several years apart, rather than burning every year.

3.3 Soil nitrogen

Nitrogen (N) is an essential element for plant growth; it is, for example, a component of proteins and nucleic acids. It is also the element that shows the greatest transfer to the atmosphere during fires (Walker *et al.* 1986a). Nitrogen, unlike other nutrients, does not accrue to soils from soil parent materials, but accumulates primarily through N_2 fixation by microorganisms in litter and the roots of some plants, particularly legumes and casuarinas, and through inputs from rainfall. Most nitrogen in surface soils is immobilised in organic form, which is not available to plants; N becomes available when it is mineralised to ammonium (NH_4^+), and then to nitrate (NH_3^-) – this is called nitrification. Plants take up nitrogen as ammonium or as nitrate (McKenzie *et al.* 2004, Turner and Lambert 2005).

Inputs and outputs of nitrogen due to burning and as a result of processes that follow a fire are complex, and net losses and gains are therefore hard to predict. For example fire may release ammonium in the short term, and may also stimulate nitrogen fixation through germination and growth of nitrogen-fixing plants (Walker *et al.* 1986a). Fire disrupts N_2 fixation in litter, but also releases phosphorus which may encourages N_2 fixation in the soil.

Although there is some variation in findings, in general it appears that soils in sites subject to frequent burning contain less available nitrogen than those which have not burnt often or recently. In the South African study described in the last section, Fynn *et al.* (2003) found a reduction in total nitrogen in the surface 6cm of soil in most burning treatments. Potentially mineralizable nitrogen was particularly impacted. This trend was confirmed by Mills and Fey (2004), who found overall lower levels of total N in soils from annually burnt plots than in fire exclusion treatments over a series of South African experiments. In Kansas, Ojima *et al.* (1994) found that available N was lower in burnt than in unburnt soils. Johnson and Matchett (2001), also working in the Kansas prairie, found lower levels of N in roots in more frequently burnt plots. In south-east Queensland, Guinto *et al.* (2001) found significantly lower levels of nitrogen in frequently burnt wet sclerophyll forest soils than in nearby areas which had remained unburnt for many years.

Fynn *et al.* (2003) believe their findings reflect a lack of replacement of nitrogen volatilized and thus lost during burning. As soil nitrogen becomes more limiting with successive fires, grass species which are particularly efficient at using N, such as *Themeda*, become dominant. Root biomass expands "as plants compensate for N limitation by exploring a greater volume of soil" (Fynn *et al.* 2003:685).

Decreases in N with burning, however, are not universal. In south-east Queensland, neither total nor potentially mineralisable nitrogen differed significantly between burning treatments in dry sclerophyll soils (Guinto *et al.* 2001). In terms of trends, nitrogen levels were higher where burns had been carried out every 2-4 years than in either long unburnt or annually burnt soils. In South Africa, Aranibar *et al.* (2003) found that although total soil N was higher in control than burn treatments in one of three sites studied, this was not the case in two other sites.

While it may seem axiomatic that higher levels of nitrogen in soils are better than lower levels, there are reasons why this may not always be so.

For example, although greater nitrogen levels might be assumed to be associated with greater grass growth, Bowman and Fensham (1991) found a very close *negative* correlation between grass cover and total soil nitrogen across an ecotone where rainforest was expanding into grassy savanna in north Queensland: more nitrogen, less grass. Prober *et al*. (2002b) found degraded sites in Western Slopes rangelands had higher soil nutrient levels, in general, than undegraded grassy woodlands. Exotic plant cover was highest in more fertile soils, particularly where nitrate was high, while *Themeda* and *Poa*-dominated reference sites had the lowest levels of nitrate. These authors believe that "Low nitrate concentrations maintained in the *Themeda australis-Poa sieberiana* system are likely to provide resistance to weed invasion" (Prober *et al.* 2002b:706) and suggest that one way to restore a healthy native understorey in degraded pastures is to break the nutrient feedback loop set up by annual exotics (which die, releasing nutrients) by regenerating perennial tussock grasses such as *Themeda*. A recent test of this proposition (Prober *et al.* 2005) found reductions in levels of both nitrate and exotics in experimental plots seeded with *Themeda*. These reductions were most impressive when *Themeda* seeding was combined with burning (two fires one year apart). Prober *et al.* (2005:1084) conclude:

> "Our results indicate that *Themeda* may be a keystone species, able to drive and maintain the soil understorey system in a low-nitrate condition that, if appropriately managed, remains resistant to weed invasion."

In the prairie experiment described above, Ojima *et al.* (1994) showed that the grasses found in the repeated burnt areas were C4 species[9] which used nitrogen particularly efficiently, ie they were able to gain more biomass of carbon per unit of nitrogen used. Plant material in these sites therefore had a high carbon to nitrogen ratio (C:N). Ojima *et al.* (1994) surmise that when these plants, and particularly their roots, die, they immobilize large quantities of nitrogen in their decomposition, setting up a feedback loop that favours species able to use N efficiently. Without fire, nitrogen builds up (Raison *et al.* 1993), and the competitive advantage then switches to C3 species – a category which includes woody plants. Ojima *et al.* (1994) conclude that plant productivity in annually burnt grasslands is maintained because of efficient nitrogen use, despite reduced levels of available nitrogen.

Johnson and Matchett (2001) take this discussion a step further. They point out that productivity in frequently burnt prairie grasslands is limited by nitrogen availability, while that of unburnt prairie is limited by availability of light, as grass growth is slowed by accumulated biomass. Their study also compared areas which had been subject to different levels of grazing (by bison). They conclude that the limiting element in heavily grazed patches is carbon, not nitrogen: grasses in grazed areas had smaller root systems, higher concentrations of nitrogen and lower C:N ratios in their root tissue than grasses in frequently burnt areas from which animals had been excluded. These findings suggest that grazing may mitigate, to some extent, nitrogen deficits resulting from frequent burning – but perhaps at the expense of benefits such as expanded root systems and carbon storage.

---

[9] Photosynthesis in grass species involves one of two metabolic pathways. In C3 species photosynthesis takes place in cells just below openings in the leaf surface called stomates, and produces as a first step a product containing three carbon atoms. In C4 species carbon is fixed in cells arranged in bundles (Kranz anatomy), and produces as a first step a product containing four carbon atoms. The C4 pathway uses CO_2 more efficiently and is favoured where light levels are high. Because C4 plants have a lesser need for open stomates, they lose less water than C3 species and so may do better in arid environments. C3 grasses often grow better in winter and are sometimes called 'cool season' grasses, whereas C4 grasses tend to grow in summer and are sometimes called 'warm season' grasses.

In summary it appears that in at least some grassy ecosystems, soils and their associated plant cover can exist in two states:

- State 1: Soils characterised by relatively low levels of available nitrogen; vegetation dominated by efficient C4 grasses such as *Themeda* with extensive root systems; limited abundance of C3 grasses, exotics and woody shrubs. This state seems to be associated with frequent burning and is unlikely to be found where grazing is heavy.
- State 2: Soils characterised by relatively high levels of available nitrogen, vegetation dominated by C3 or less efficient C4 grasses; higher abundance of C3 grasses, exotics and woody shrubs. This state seems to be associated with fire exclusion and low fire frequencies, and may also be promoted by heavy or continuous grazing.

Fire and soil nitrogen

- Nitrogen is the element most readily lost to the atmosphere in a fire.
- Studies have found lower levels of available nitrogen in soils where burning has been frequent, relative to soils where burning has been rare or has not occurred for a long time.
- Frequent burning encourages C4 grass species which use nitrogen efficiently, such as *Themeda australis*, and may also encourage these grasses to expand their root systems.
- Without fire, in many environments levels of available nitrogen in soils build up, encouraging C3 grass and herb species, exotics and woody plants.
- When a fire follows a long period without fire, available nitrogen levels may 'spike' in the short-term, reinforcing the existing C3 species complement.
- A precautionary approach to maintaining moderate levels of available nitrogen under regular burning might involve:
    - Burning at 2-5 year intervals rather than annually
    - Use of longer intervals in some parts of the landscape to encourage a mix of summer and winter grasses.

It is also worth noting that when a fire occurs after a long interfire interval, available nitrogen levels may be greatly elevated short-term (Ojima *et al.* 1994, Prober *et al.* 2005). Thus a single fire in the second state described above is more likely to reinforce this state than to push it towards State 1.

Might there be an intermediate level of fire frequency – and perhaps of grazing pressure – which would maintain moderate levels of available nitrogen in soils, efficient deep-rooted perennial C4 grasses like *Themeda,* together with a mix of other grasses including C3 species and herbs (which also use the C3 metabolic pathway)? Results from Bauple (Guinto *et al.* 2001) and the findings of Fynn *et al.* (2003) suggest that spring burns at 2-4 year intervals may maintain nitrogen levels. Longer intervals in some parts of the landscape might help provide a mix of summer and winter grasses.

3.4 Other soil nutrients

Some other soil nutrients appear to occur in greater quantities in soils in frequently burnt areas relative to those in areas left unburnt, although differences are small. For example Abbott *et al.* (1984) studied dry sclerophyll forest soils in Western Australia: burnt soils had been exposed to a fire every 2-3 years for 45 years, while soils in the unburnt treatment had not experienced any fire during that time. Most nutrients, including phosphorus (but not nitrogen), were found in higher concentration in the burnt sites, however differences were not significant, possibly because statistical power was low (Abbott *et al.* 1984). In Victoria, Adams *et al.* (1994) found higher concentrations of available phosphorus in frequently burnt heathland soils than in soils in matched plots which had not been burnt for 40 years. Phosphorus availability was also significantly greater in a frequently burnt dry grassy forest sites in south-east Queensland (Guinto *et al.* 1998). Potassium was also higher in frequently burnt soils, although not significantly so (Guinto *et al.* 2001).

One way to assess the overall effects of increases and decreases in various soil nutrients is to measure plant growth in a controlled environment. Guinto *et al.* (2002) grew eucalypt seedlings in pots containing soils from the south-east Queensland fire experiments mentioned throughout this discussion of soil nutrients. They found no significant differences in biomass between seedlings grown in frequently burnt soils and those grown in soils where fires had not occurred for 21 years. When they measured nutrient levels in the experimental seedlings, they found frequent burning associated with higher levels of phosphorus (significantly so for dry sclerophyll forest, but not wet sclerophyll forest, soils), while no burning was associated with higher levels of nitrogen (significant for wet sclerophyll forest, but not dry sclerophyll forest, soils). These trends in plant tissue are similar to those noted above for the soils themselves. The authors concluded that frequent long-term burning had had no deleterious impacts on seedling growth, so far.

However McIntosh *et al.* (2005) argue that burning over very long time periods (approx 34,000 years) in Tasmania has led to profound changes in soils in this state relative to those in New Zealand where anthropogenic burning has only been a factor for 800 years. Tasmanian soils under dry forests in Tasmania have lower exchangeable calcium + magnesium + phosphorus values than soils under wet eucalypt forests, and higher C:N ratios, whereas New Zealand soils in similar locations in the landscape show the opposite trend.

Fire and other soil nutrients

- Although evidence is scanty, it appears that moderately frequent burning does not deplete most soil nutrients over a time-scale of decades to centuries.
- There is some suggestion that burning regimes over tens of thousands of years may have influenced the nutrient status of soils in some parts of Australia.

3.5 Soil microfauna and microbes

Soil microorganisms (bateria and fungi) have many functions, and are particularly important in decomposition and nutrient cycling. While there are many ways in which they may be affected, directly or indirectly, by fire, research on this topic is virtually non-existent. A recent review concludes that the indirect effects of fire, particularly on vegetation composition and structure, are likely to be the most important drivers of the interaction between soil microbial activity, plants and fire regimes (Hart *et al.* 2005). One study which did include microbes was the South African study that has already been described. Fynn *et al.* (2003) found no effect of burning on microbial biomass in the top 2cm of soil. In the 4-10cm layer, microbial biomass was greater in annually burnt plots than where fire had been excluded.

Soil microfauna. [I may be able to expand this section – may be able to find additional literature.] In Australia, Neumann and Tolhurst (1991) assessed the effects of a single planned burn on populations of earthworms in long-unburnt dry sclerophyll forest in Victoria. Earthworm populations were temporarily depressed after a spring burn, which in Victoria was followed by a hot, dry summer, but were unaffected by an autumn fire followed by good rainfall.

3.6 Erosion and infiltration

The fact that fires can be associated with accelerated soil erosion is well documented (eg Good 1973, Atkinson 1984, Prosser and Williams 1998[10], Dragovich and Morris 2002). There appear to be two primary reasons why this is the case. First, fires remove protective vegetation and surface litter which normally shields the soil from being broken up by raindrops and slows overland movement of water which can carry soil away (Gilmore 1968, McIvor *et al.* 1995). Second, heating can cause soils to become abnormally water repellent or hydrophobic. This condition, which has been found following fire all over the world, arises when organic substances are vaporized then condense further down the soil profile to form a layer which resists infiltration. Water repellent soils are prone to erosion through rill formation and raindrop splash (DeBano 2000). Water infiltration is impacted by loss of cover as well as by hydrophobia. Litter cover is associated with improved physical condition of the

[10] This article includes a literature review and a model of the effects of fire on erosion as well as results from a field experiment, and provides a good introduction to the topic of the effects of fire on runoff and erosion.

soil surface, and impedes water movement thus allowing more time for infiltration (McIvor *et al.* 1995). Water-repellency limits the places where water can infiltrate, although patchiness in the hydrophobic layer generally still allows water to get through to the subsoil at some points (DeBano 2000).

Studies also clearly indicate that the more intense or severe the fire, the more erosion and hydrophobia are likely to occur (Prosser and Williams 1998). Cover losses are greater in more intense fires. For example in a study following fires of low and moderate intensity in Victoria, Adams and Simmons (1996) found much more bare ground, considerably lower vegetation cover and slower litter build-up in the more severely burnt area for a number of years post-fire. The severity of water repellency and its duration post-fire also increase with fire intensity (DeBano 2000). In a study of areas burnt at low, moderate and high intensity in the Blue Mountains, Dragovich and Morris (2002) found eight times more sediment movement in a moderately burnt site than in a similar site which had burnt at low intensity (this area had had been burnt two years previously for fuel reduction), while 15 times as much sediment was collected where fire intensity had been high.

However even after intense fires, erosion may only become a problem in some areas, and after heavy and prolonged rainfall events (Atkinson 1984, McIvor *et al.* 1995). Some soils are more prone to erosion than others: coarse soils with good porosity are not as erosion-prone as fine-grained soils (Gilmore 1968). Steep slopes may be particularly prone to post-fire erosion, as is land that has reduced cover due to heavy grazing (Good 1973, McIvor *et al.* 1995). Cleared areas such as hastily-constructed fire trails and tracks are prone to severe erosion (Gilmore 1968, Good 1973, Atkinson 1984). In intact bushland, soil material may be mobilised during heavy rainfall, but may not travel far before being stopped by debris dams and the roots and stems of remaining and regenerating vegetation (Good 1973, Atkinson 1984). Prosser and Williams (1998) found no evidence of soil moving out of a catchment burnt at moderate intensity even though local movement was recorded.

Few studies have addressed the effects of differing fire frequencies on erosion and infiltration. There are reasons to suspect, however, that very frequent burning could be associated with decreased infiltration and accelerated soil erosion. Mills and Fey (2004) found that soils from annually burnt plots in long-term burning experiments in South Africa had significantly lower rates of infiltration in the laboratory and were prone to crusting. These authors argue strongly that frequent burning is likely to have a negative impact on infiltration rates in the field, for example because decreased organic matter in the top 1cm of the soil may result in reduced aggregation, freeing clay particles to block pores near the soil surface when it rains. Certainly each time litter is removed, soil is exposed to erosive influences.

However there are also aspects of regularly burnt landscapes that might be expected to minimise erosion relative to what might occur when the same landscape burns after a long interfire interval. When fires occur every few years they are likely to be less intense than a fire after a long interval because fuel loads will tend be lower (eg Fox *et al.* 1979, Morrison *et al.* 1996, Watson 2005). Also management fires can be timed for weather conditions compatible with a low severity fire, whereas landscapes which are not subject to management fires are likely to burn, when a fire does occur, under the more extreme conditions which are often associated with wildfires (Bradstock and Gill 2001). As already noted, field studies show much greater levels of erosion after high and moderate intensity fires than where fire intensity is low. In grassy ecosystems regular burning encourages tussock grasses with deep roots which may help water to infiltrate (Section 2.1.5). These grasses recover rapidly post-fire: Morgan (1996) found cover in a *Themeda* grassland in Victoria was 84% by 4.5 months

Fire, erosion and infiltration

- Fires can lead to accelerated erosion because:
  - Fires remove protective vegetation
  - Heating can cause soils to become abnormally water repellent.
- Fire intensity influences the extent of erosion and problematic water repellency: the likelihood of each increases with fire intensity.
- Even after an intense fire, erosion may be minimal. Risk factors include heavy and prolonged post-fire rainfall, steep slopes, fine-grained soils, and previous cover reduction as a result of heavy grazing. Cleared areas such as fire trails and tracks are very erosion-prone.
- Little is known about the effect of regular burning on erosion and infiltration.
  - Frequent burning may encourage erosion and reduce infiltration through regular removal of litter cover. But on the other hand,
  - Frequent burning may limit fire intensity and thus limit, in turn, its negative effects on erosion and water repellency.
  - Frequent burning may encourage deep-rooted tussock grasses which provide cover rapidly after a fire and may help water to infiltrate.
- A precautionary approach to issues around erosion and infiltration in grazed native vegetation in the Northern Rivers might involve:
  - Regular burning in patches across the landscape to break up fuel loads and reduce chances of high intensity wildfire
  - Burning at 2-5 year intervals rather than annually to promote deep-rooted grasses but also allow time for litter incorporation
  - Burning in spring rather than autumn to encourage litter incorporation over winter and rapid post-fire grass growth to quickly re-establish cover
  - Burning under weather conditions conducive to relatively 'cool' burns
  - Allowing grass cover to develop before turning stock on to burnt areas.

post-fire, while a 2 year old sward had 100% grass cover and a cover repetition score of 5.0 (Morgan 1998a). Water repellency is also greater when fires are severe; in fact in a comprehensive review DeBano (2000) recommends regular management fires as the only practical solution to the problem of hydrophobia and associated erosion in wildland environments.

A precautionary approach to issues around erosion and infiltration in pastures in Northern NSW might again involve avoiding annual burning. Fires at somewhat longer intervals would allow some litter to build up and become incorporated into the soil while still promoting deep-rooted tussock grasses, reducing the chances of intense wildfire, and allowing for low intensity management burns. Spring burns timed so grasses grow quickly as rainfall and temperate increase may be more effective at limiting erosion than autumn burns that leave paddocks bare over winter. Allowing grass cover to develop before turning cattle on to burnt areas is also likely to assist (McIvor 2002).

3.7 Summary and implications

The research reviewed in this section suggests that while frequent burning does not necessarily compromise soil health in the medium term, and may even have some benefits, there may also be risks associated with this practice. Trade-offs may therefore be inevitable.

Relative to soils not subject to burning, regularly burnt soils may have:

- Lower levels of organic matter in upper soil layers, but higher levels further down the soil profile due to expanded root systems (Section 3.2).
- Lower levels of available nitrogen, and
- A species complement dominated by C4 grass species able to use nitrogen efficiently. These grasses may develop deep roots as they seek out the small amounts of nitrogen that are available (Section 3.3).
- A lower abundance of native C3 grasses, exotic herbs and woody species which benefit from the higher nitrogen levels often associated with reduced fire frequency (Section 3.3).
- Somewhat higher levels of phosphorus, and comparable levels of most other nutrients (Section 3.4).
- Increased vulnerability to erosion due to reduced litter cover, but
- Decreased vulnerability to erosion due to reduced risk of intense fire, and the protective effects of fast-growing, deep-rooted tussock grasses (Section 3.6).

Several factors suggest that where use of fire is a regular aspect of land management, annual burns may be less desirable than somewhat longer intervals of, say, 2 to 5 years. Relative to annual burns, variable intervals between these thresholds:

- Would allow more time for organic matter to be incorporated into the soil (Section 3.2).
- Might encourage somewhat higher levels of available nitrogen in the soil while continuing to promote deep-rooted C4 tussock grasses, perhaps along with a more diverse mix of C3 grasses and herbs (Section 3.3).
- Would allow some nitrogen-fixing shrubs – peas, wattles and casuarinas – to continue to occur in the landscape (Section 4.5.4).
- Would allow time for earthworms and other soil microfauna impacted by fire to recover (Section 3.5).

- Might reduce the potential for erosion through greater retention of litter and grass cover (Section 3.6).

The available evidence also suggested that spring burns may be more conducive to soil health than autumn or winter burns. As most rainfall in the Northern Rivers region falls in summer, spring burns are more likely to be followed by good growing conditions than autumn burns. Relative to autumn burns, spring burns:

- Would allow dead grass to be incorporated into the soil over winter. In the South African experiment described in Section 3.2 spring burns were associated with higher soil carbon in the upper soil layers, probably for this reason. These burns were timed to occur just after the first good spring rain of the season (Fynn *et al.* 2003).
- Would probably encourage faster recovery of soil microfauna (Section 3.5).
- Would usually be followed by quicker recovery of grass cover, which in turn should minimise erosion risk, encourage infiltration, and minimise evaporation (Section 3.6, Lodge *et al.* 2001).

The desirability of re-establishing grass cover to minimise erosion also suggests that where possible, immediate and/or heavy stocking after fire should be avoided (Section 3.6, McIvor 2002).

Fire and soil health – key points

- While frequent burning does not necessarily compromise soil health, and may even have some benefits, it may also have some risks. Trade-offs may be inevitable.
- Where fire is a regular aspect of land management, several factors suggest that burning at intervals of around 2-5 years will probably have better outcomes for soil health than annual burning.
- Available evidence also suggests that spring burns may be more conducive to soil health than fires in autumn.

4 ON-FARM BURNING: REASONS, REGIMES, RESULTS

Why do graziers burn? This section explores a range of reasons for burning, and asks what evidence exists to support the effectiveness of fire in meeting each goal. Fire regime characteristics which might be associated with greater or lesser effectiveness are discussed. Aims addressed in this section include:

- To covert rank grass to palatable 'green pick' (Section 4.1)
- To attract animals to particular areas (Section 4.2)
- To maximise grass production (Section 4.3)
- To encourage particular ground layer species (Section 4.4)
- To manage shrub and tree abundance (Section 4.5)
- To prevent wildfire burning out large areas (Section 4.6), and
- To encourage native plant and animal species (Section 4.7).

4.1 To convert rank grass to palatable 'green pick'

In the Northern Rivers region the base stocking rate on grazing properties is determined by the carrying capacity of the country in spring. This means that when good rain falls in summer, cattle are unable to keep up with growing grasses, which become rank and unpalatable as a result. Thus the primary motive for burning in native pastures is to remove rank grass and encourage nutritious new shoots (Tac Campbell, pers. comm. 2005).

Historical records indicate that burning for green pick has a long tradition in the Northern Rivers region. Lismore environmental historian Brett Stubbs (2001) quotes the 19th century 'economic botanist' Fred Turner, who advocated burning blady grass and swamp foxtail pastures annually in October or November to produce " 'a capital growth of succulent herbage during the greater part of summer, which cattle eat with avidity' " (Stubbs 2001:310). Frequent burning for green pick is also a long-standing practice in grazed grassy ecosystems in other parts of Australia, for example in the tropical savannas (Andrew 1986).

Although no studies from the Northern Rivers region were located, there is evidence from a wide range of environments that burning temporarily increases nutrient content in native pasture species. Robertson (1985) found that burning dramatically increased nutrient levels in *Themeda australis* and also in other grasses in a Victorian grassy woodland. Differences could be seen up to 18 months after fire. Winter (1987) ascertained that new growth of perennial grasses including *Themeda* in the semi-arid tropics in the Northern Territory had considerably higher nutrient content than unburnt pastures. The 'spike' of increased nutrients in this experiment was mostly short-lived: levels were similar to those in unburnt vegetation by nine months post-fire. Leigh *et al.* (1991) found that burning increased forage quality (crude protein and/or dry matter digestibility) in four sub-alpine grass species, including *Poa sieberiana*. This effect was short-lived in the two *Poa* species tested, although it lasted into the second post-fire year for *Danthonia pilosa* and another subdominant grass. Ash *et al.* (1982) found a higher proportion of green leaf, and higher nitrogen levels, in burnt relative to unburnt native pasture in south-east Queensland after an October burn, although again big differences were only apparent in the first few months.

The benefits in terms of animal weight gain from feeding on green pick are less clear – and are also less studied. In south-east Queensland Ash *et al.* (1982) found cattle in burnt pasture had superior weight gain to those in unburnt pasture in the first three months after fire, but this situation was reversed in the second three months. Overall weight gain after nine months was marginally, but not significantly, greater in burnt pasture. Winter (1987) found that cattle feeding on burnt ground in the Northern Territory benefited in terms of weight gain in some seasons but not others (early wet, and late dry seasons in these tropical pastures). Additional mineral supplementation improved weight gain considerably in burnt pastures. Fuhlendorf and Engle (2004) found no differences in weight gain between animals grazed on burnt and unburnt prairie pastures in the US.

The nutritional benefits of burning and their short-lived nature suggest that if production of green pick was the only aim of pasture management, annual or biannual burns would be the preferred regime. The equivocal results for animal weight gain however suggest that other factors, such as grass biomass production (Section 4.3) and species composition (Section 4.4) may also be important.

4.2 To attract animals to particular areas

Does burning provide a low-cost method of moving animals around a property or paddock?

Research findings support the contention that both cattle and native grazing animals prefer to feed in recently burnt areas. Fuhlendorf and Engle (2004) found that cattle preferentially grazed burnt patches in an Oklahoma prairie. Robertson (1985) reports that kangaroos chose young green grass leaves in burnt areas in eucalypt woodland in Victoria. Andrew (1986) found that cattle preferentially grazed burnt ground in *Themeda* savanna in the Northern Territory, although they spent less time in the burnt area as the season progressed and burnt grass became rank. In a local study Southwell and Jarman (1987) found Eastern Grey Kangaroos and Red-necked Wallabies made significantly greater use of burnt areas on a property in the Clarence River Valley. Cattle appeared to have similar preferences although there was insufficient data for analysis.

Fire and 'green pick'

- Research shows that burning does increase the nutrient content of native pasture species.
- While some studies have found increased nutrient levels for up to two years after a fire, in others the effect lasted only a few months.
- Studies of animal weight gain from feeding on burnt pastures, however, suggest benefits may be marginal.
- Research shows that cattle, and other grazing animals, prefer to graze on burnt ground, and may graze in a less patchy fashion after a fire. So fire may indeed provide a means to move stock around, and may also help spread grazing pressure.

Archibald and Bond (2004) monitored grazer distributions over three years in a wildlife park in South African. Animals were attracted to burnt areas, and this resulted in reduced grazing pressure in unburnt areas. Grazers were more dispersed in burnt than in unburnt areas, which were grazed patchily. They concluded that fire may be helping to spread grazing pressure more evenly across the landscape, and thus to reduce it at any one point.

4.3 To maximise grass production

Does fire help maximise grass production? This question can be approached from several angles. Component questions include:

- Is grass biomass production after a single fire greater than it would be if a fire had not occurred?
- Is grass production in frequently burnt areas greater than in areas where fire does not occur, or occurs rarely?
- What about long-term effects of frequent burning? What happens to soil resources in pastures where fire is or is not used? This question is important because soil health affects long-term productivity.

The first and second of these questions are addressed in this section. The question of longer-term effects of fire on soil resources has already been addressed in Section 3.

4.3.1 Does a single fire encourage biomass production?

Obviously, immediately after a fire there will be a decrease in grass biomass, because fire consumes grass. While there is evidence that fire does encourage biomass production in grassy vegetation (see below), the advantages must be considered in the light of the temporary loss of feed. While this may not be problematic in a good year, when drought follows widespread burning the burnt-off feed may be sorely missed. And as Tothill (1992:276) points out, the availability of supplements mean that “no longer is the accumulation of low quality unused herbage the embarrassment that it used to be.”

The evidence for increased biomass production after a single fire includes, unusually, a local study from grazing country in the upper Clarence River valley. Southwell and Jarman (1987) measured the biomass of four categories of grassy vegetation several times over a 14 month period after fire, and compared these figures with those from matched control plots that had not been recently burnt (although as overall fire frequency in this landscape was estimated to be about 2.5 fires per decade, control plots may not have been all that long without a fire). This study, on land grazed by both cattle and macropods, found that the biomass of “other grasses”, a category which in native pasture was dominated by *Themeda australis*, exceeded control levels by 7 months after burning and continued to increase over the remaining 7 months of the study. “Tussock grass” (mostly *Poa* species), and blady grass biomass were marginally below control levels by 14 months post-fire, while herb biomass in burnt plots exceeded that in control areas by about 9 months post-fire. Note that cattle and native herbivores were present throughout this study, which found preferential grazing occurring in burnt plots. Biomass levels thus represent what remained after removal by grazing, and more was removed in burnt areas.

At the level of individual species, Leigh *et al.* (1991) found an increase in standing biomass after burning in two of four subalpine grass species tested. Where plants were also subject to simulated grazing through cutting, regrowth in burnt plants was much greater than in plants that had not been burnt.

4.3.2 Does regular burning encourage biomass production?

Does a series of regular burns encourage grass production? Again, there is evidence from Northern NSW that this is the case. A number of researchers report decreased levels of grass cover as fire frequency declines.

Fire and grass production

- Fire consumes grass, so grass biomass is of course initially reduced by a burn. It is thus unwise to burn all rank feed at once, in case drought reduces post-fire regrowth to unsustainable levels.
- Research from the Clarence River Valley found that in regularly burnt pastures, biomass of native grasses in burnt areas reached or exceeded levels in unburnt patches by 7 to 14 months after a fire. This was despite preferential grazing in the burnt areas.
- Several Northern Rivers studies have found higher levels of grass biomass in frequently burnt forests than in similar forests where fire has been infrequent or has not occurred for some time. Grass abundance appears to increase with increasing fire frequency.
- There is some evidence that animal weight gain in regularly burnt pastures exceeds that on unburnt pastures.
- Overall, regular burning does appear to increase grass production short-term, and may play a vital role in retaining abundant grass cover in the longer term in productive forest landscapes.

Kitchin (2001) studied effects of fire frequency in Guy Fawkes National Park, in both Tablelands wet sclerophyll forests and dry sclerophyll forests in the gorges of the eastern escarpment. Grass cover in wet sclerophyll forests was greatest where fire frequency was high (6+ fires in 25 years) or where there had been at least one very short (1-2 year) interfire interval, and declined with decreasing fire frequency and increased length of interfire interval. In the dry forests of the escarpment gorges, very high fire frequencies were not encountered. Here, grass cover was highest where there had been 2-4 fires in 25 years, including a least one short (1-3 year) interfire interval, and lowest in the category with the longest time-since-fire and interfire interval. Other local researchers also report a decrease in grass cover as fire frequency declines (Birk and Bridges 1989, Tasker and Dickman 2004, Doug Binns, pers. comm. 2005, John Hunter pers. comm. 2005). Declines in grass biomass with decreased fire frequency may be the result of increased competition from trees and shrubs (Section 4.5.2), suppression by heavy litter loads, decline of grasses such as *Themeda* due to self-shading (Morgan and Lunt 1999), and/or decline of C4 species due to increased soil nitrogen (Section 3.3).

Does this increase in herb biomass with regular burning translate into animal weight gain? A three-year experiment in black spear grass country in South-east Queensland which compared weight gain in cattle grazed on regularly burnt pastures (the researchers aimed for annual burns, however in some years there was too little fuel for effective burning to take place) found that overall, animals gained 12% more weight on burnt than on unburnt pastures. There was, however, a lot of year to year variation in the magnitude of the difference between treatments (Tothill 1992).

4.4 To encourage particular ground layer species

4.4.1 Benefits of native tussock species

Graziers are becoming increasingly aware that pasture quality is a function of plant species composition, and that grass and forb species interact in dynamic ways in response to two major ecosystem processes in pastures, grazing and fire (Johnston 2000).

In native pastures, a wide diversity of grasses and herbs helps ensure some species will grow well and maintain production in a range of seasonal and climatic conditions (McIntyre *et al.* 2001). At a paddock level, both 'lawn' patches with low-growing species, and tall tussock patches, contribute to pasture productivity and sustainability (McIntyre *et al.* 2000). At a species level, both summer-growing species which use the C4 metabolic pathway, such as *Themeda australis*, *Sorghum leiocladum* and *Capillipedium* species, and winter-growing/all year round C3 species like *Microlaena stipoides*, *Poa* and *Austrodanthonia*, have a place in maintaining pasture diversity.

Recent research suggests that large C4 tussock grasses are particularly important for maintaining soil condition and ecosystem function (Section 2.1.5). Benefits attributed to perennial tussock grasses include:

- Superior ability to incorporate organic matter into the soil (Derner *et al.* 1997).
- Ability to capture and redistribute nutrients (Williams *et al.* 1997, McIntyre *et al.* 2000 and references therein, McIntyre and Tongway 2005).
- Capacity to stabilise the soil surface and minimise erosion (McIntyre and Tongway 2005).
- Ability to encourage water to infiltrate into the soil (McIntyre and Tongway 2005) where it can be used for plant growth, rather than running off (Fuls 1992).
- Capacity to limit deep drainage and associated acidification. Because C4 grasses grow in summer, they draw water out of the soil through photosynthesis during the hot, wet months, and take up available nitrogen. Native C3 perennials tend to limit their growth, and thus their uptake of water and nitrate, in hot weather (Johnston 2000). McIvor *et al.* (2005) found lower levels of nitrogen and phosphorus, and higher pH, under tall grassland patches than in 'lawn' patches dominated by creeping grasses.
- Capacity to reduce the rate of spread of invasive exotic grasses such as *Nassella neesiana* (Chilean Needle Grass) (Lunt and Morgan 2000).

Because of these benefits, CSIRO researchers advocate retaining tussock grass dominance over 60-70% of native pastures (McIntyre *et al.* 2000, 2001, 2002a; McIntyre and Tongway 2005).

4.4.2 Using disturbance to manipulate pasture composition

Pasture management for particular species composition is increasingly being advocated (Johnston 2000, Kemp 2000). The idea is to use disturbance to target unwanted species when they are weak, while also using strategies to encourage wanted species. Plants are most vulnerable when flowering, germinating, as seedlings, and when regenerating from buds (Walker and Tothill 1992, Kemp 2000). Disturbance at these points in a plant's lifecycle should decrease its abundance, while lack of disturbance at these points should help it to increase. If disturbance is to be useful in manipulating species composition, timing of vulnerable lifestages needs to vary between more and less desirable species. A sound knowledge of the flowering, recruitment and growth patterns of individual species is needed to exploit these opportunities.

Lodge and Whalley (1985) demonstrated how effective this strategy can be through a series of experiments on the Northern Slopes. These researchers reduced the abundance of *Aristida ramosa* through crash grazing when these plants were flowering, while wallaby grass was encouraged through resting paddocks temporarily while this species flowered and set seed.

Fire, as well as concentrated grazing pressure, is a potential tool for manipulating species composition: fire followed by grazing, or fire alone, may be useful. Many grasses and forbs flower rapidly after fire, and flowering may be particularly profuse at this time (Leigh *et al.* 1991, Lunt 1994, Morgan 1996, Watson 2005). The gaps created by fire are important for seedling establishment in grassy vegetation (Morgan 1998a, Morgan 2001, Watson 2005). Additionally, fire cues (heat and smoke) enhance germination in some grass species (Read *et al.* 2000, Wood 2001, S. Clarke 2003). The early year or years after fire may therefore represent a time of heightened vulnerability for unwanted species, and an opportunity for recruitment for desired species.

Fire has been used to manipulate species composition in several locations in Australia. In the Burnett region of Queensland a series of annual spring burns dramatically increased abundance of *Heteropogon contortus* (Black Spear Grass) while at the same time reducing cover of less-palatable *Aristida* species (Shaw 1957, Paton and Rickert 1989, Orr *et al.* 1991, Orr *et al.* 1997). Spring burning stimulated recruitment in *H. contortus* probably through encouraging greater seed production, promoting germination, and creating gaps (Shaw 1957, Tothill 1969, Orr *et al.* 1991). In a replicated trial of various seasons and frequencies of burn in central Queensland Walker *et al.* (1992) found that *Heteropogon* was encouraged by late dry season burns every three years, while *Themeda* benefited from early dry season burning every one, or every three, years. In the Northern Territory fire is used to reduce annual weeds by burning after they germinate but before they have time to set seed (Starr, nd). Two spring burns one year apart reduced the abundance of exotic annual grasses in central NSW (Prober *et al.* 2004).

Experimental studies have shown that some grass and forb species thrive under frequent burning, while others do not. C4 tussock grasses in general, and *Themeda australis* in particular, appear to be encouraged by fire. In the study on the New England Tablelands mentioned in the last section (Kitchin 2001), high fire frequency sites in grassy forests on the New England Tablelands were dominated by tussock grasses *Themeda australis, Poa sieberiana* and *Sorghum leiocladum* (Kitchin 2001). Here, *Themeda* cover declined sharply in plots with no short interfire intervals. Sedges and rushes were more abundant where fire had not occurred for a long time and where interfire intervals were relatively long. Studies elsewhere in NSW (Watson 2005), in Victoria (Lunt and Morgan 1999b) and in South Africa (Uys *et al.* 2004, Fynn *et al.* 2005) have also recorded considerably more *Themeda* in frequently than in infrequently or long-unburnt areas. Additional studies have documented a decline in abundance and vigour of *Themeda* with increasing time-since-fire (Robertson 1985, Morgan and Lunt 1999, S. Clarke 2003). Fire may therefore play a useful role in the regeneration and retention of C4 tussock species which, as noted above, are important for long term pasture sustainability. Winter-growing native species (C3 species) may be more fire-sensitive, however they too can recover well after a fire (McGowen 2003). *Poa sieberiana*, in particular, can increase under frequent burning (Tasker 2002, Kelly 2004).

4.4.3 Effects of post-fire grazing

Unfortunately, this scenario becomes more complicated when the interaction between grazing and fire is considered. In the Black Spear Grass experiments reported above, an increase in the abundance of the desirable *Heteropogon contortus* only occurred where pastures were ungrazed after the burns (Orr *et al.* 1991, 1997). This was because cattle selectively grazed regenerating *H. contortus* plants. Research to explore the degree to which grazing pressure would need to be reduced post-fire in order to obtain beneficial changes in species composition found that a 4 to 6 month rest period, or half stocking, led to better results than if paddocks were grazed immediately after burning, or only rested for two months (Orr and Paton 1997).

Several native Northern Rivers tussock grasses, including *Themeda australis* and *Sorghum leiocladum* decrease with domestic grazing (Vesk and Westoby 2001, Chilcott *et al.* 1997, Section 2.1.5). It is therefore likely that the situation described above for *Heteropogon* will apply to these species: while fire may have the potential to enhance their abundance, heavy grazing of post-fire regrowth may well negate these benefits (McIvor *et al.* 2005). There is little research to guide decisions as to what post-fire stocking rates, or what rest period, would ideally apply. *Themeda* was found in one of the treatments studied by Orr and Paton (1997). In this half-stocking treatment, kangaroo grass abundance increased dramatically over the first three years of annual burns, even with light grazing, then dropped back somewhat after burns and light grazing in years 4 and 5.

Northern Rivers graziers wishing to enhance the abundance of *Themeda* and other tall tussock grasses in native pastures would probably do well to either spell them for several months after burning, or keep post-burn stocking relatively low. Ensuring opportunities for *Themeda* to flower may be important – and this may occur quite a few months, or even up to 18 months, after fire (pers. obs.). Flowering in *Themeda* is greatest in the early post-fire years, then declines considerably after about five years post-fire (Morgan and Lunt 1999). Recruitment in native grassland species can continue for several years after fire (Morgan 2001). Thus although some of the experiments described above used annual burns, somewhat less frequent fires may be better for encouraging *Themeda* and other native tussock species.

4.4.4 Blady grass and bracken

Finally, some thoughts about fire, grazing, blady grass and bracken.

It is often assumed that bracken and blady grass increase with frequent burning, however not all sources of evidence support this contention. Tasker (2002) did record greater cover of both blady grass and bracken in more, relative to less, frequently burnt areas in wet sclerophyll forest on the Northern Tablelands, although the tussock grass *Poa sieberiana* was more abundant than either in frequently burnt sites. Also on the Tablelands, Kitchin (2001) found that blady grass was most abundant on moderate fire frequency sites with at least one short interfire interval, however it was also abundant where fire had been absent for at least 25 years. Bracken (*Pteridium esculentum*) was most abundant in long-unburnt sites, and least abundant where fire frequency had been high. Again on the Tablelands, Watson and Wardell-Johnson (2004) found no association between the abundance of either blady grass or bracken and either time-since-fire or fire frequency.

Encouraging particular ground layer species

- Both fire and grazing can be used to manipulate species composition in pastures.
- Undesirable species can be targeted when they are vulnerable, eg when flowering and when seedlings are germinating. Desirable species can be given opportunities to recruit.
- A sound knowledge of species life histories is needed to exploit these opportunities.
- Fire enhances flowering and recruitment in many herbaceous species, and so may represent a time of increased vulnerability in unwanted species, and of increased opportunity for recruitment in desired species.
- Some native species, including C4 tussock grasses such as *Themeda*, thrive under frequent burning, while others increase in the absence of fire. Fire may therefore play a useful role in the regeneration and retention of native tussock grasses.
- Unfortunately, these species tend to decrease with grazing, so if the aim is to promote them, resting or reduced stocking in the months following fire is probably advisable.
- Research into the differential effects of fire and grazing regimes on the dominant native grasses of the Northern Rivers region is virtually non-existent. Landholders are therefore encouraged to take an 'adaptive management' approach.

It is possible that blady grass may come to dominate in paddocks where kangaroo grass and other native tussock species have been grazed out, giving the impression of a fire effect. Unfortunately no experimental studies of the effects of different fire and grazing regimes on bracken and blady grass relative to other grasses were located.

4.4.5 Adaptive management

The scope for research to inform attempts to use fire and/or grazing to manipulate species composition is very broad: there are so many species, so many possible fire regimes, grazing regimes, and combinations thereof, and so many different environmental conditions. This research is only just beginning, and has not directly addressed the dominant grass species found in Northern Rivers native pastures. In particular, science has yet to provide clear guidance as to what fire and grazing regimes might promote a more diverse complement of C4 tussock grasses and C3 herbs, over blady grass and bracken.

Landholders interested in using fire and grazing to manipulate species composition will therefore need to experiment, monitor outcomes, and adjust strategies as partial answers come to hand.

4.5 To manage shrub and tree abundance

> "The need to maintain trees in the rural landscape is now rarely disputed. Eucalypts have aesthetic and cultural values, as well as utilitarian ones – providing timber, shade and habitat as well as hydrological functions. Trees also contribute to nutrient cycling, and their presence in woodlands creates micro-habitat diversity in the ground layer… which provides niches for invertebrates and plants" (McIntyre *et al.* 2000:96).

Shrub and tree density varies enormously across North Coast landscapes. On grazing properties, there is a place for both trees and shrubs. Most graziers, however, are likely to want to set some limits on canopy and mid-storey thickness, as these factors influence grass biomass and ground layer composition (see below). It's all a question of balance.

As well as the aesthetic, cultural and biodiversity values mentioned above, trees and shrubs have practical uses (McIntyre *et al.* 2000, Tac Campbell pers. comm. 2005):

- Trees and shrubs help maintain populations of birds and insects, which have a role in reducing pests and in pollination
- Trees and shrubs reduce the impact of frost
- Trees provide shelter and shade for stock
- Trees and shrubs supply structural support to river and creek banks
- Trees help control salinity
- Trees provide timber and firewood
- Some native shrubs and trees fix nitrogen

CSIRO researchers recommend that at least 30% of property area should be covered with trees (McIntyre *et al.* 2002b). This is because fauna species such as woodland birds and insects often need minimum amounts of habitat to survive, so good-sized woodland areas are needed. Also trees do better in groups than when they're isolated. Within wooded areas, McIntyre (2002) recommends an on-farm tree density of around 30 trees per hectare. This recommendation is based on work by Prober and Brown (1994), Benson and Redpath (1997), and Lunt (1997b), and reflects both ecological recommendations and 'best estimates' of pre-European tree density. Whether tree density before European settlement was similar across grassy vegetation types is not known. Thirty trees per hectare is quite a low density relative to that now found in coastal grassy woodlands near Sydney (Benson 1992, Watson 2005). Post-logging regrowth may be denser than original stands; stands may self-thin as they age.

In the sections below I first consider the influence of trees and shrubs on soils, grass production and pasture composition (Sections 4.5.1 to 4.5.3). The effects of fire on shrub abundance, and on recruitment and health of eucalypts are then explored (Sections 4.5.4 to 4.5.6). Material in these sections is summarised in Section 4.5.7.

4.5.1 Do trees and shrubs influence soils?

The answer to this question is that often, they do.

Many researchers have found higher nutrient levels under trees or large bushes than in open areas (Robertson 1985, Tongway and Ludwig 1990, Hobbs and Atkins 1991, Jackson and Ash 1998, 2001, Prober *et al.* 2002a,b, Aranibar *et al.* 2003). For example on the New England Tablelands Chilcott *et al.* (1997) found significantly higher levels of total nitrogen and phosphorus and greater microbial activity in forest sites than in open paddocks without trees. Proposed mechanisms for nutrient build-up include long-term accrual from litter (Gleadow and Ashton 1981), interception of nutrient-rich dust by the canopy, concentration of nutrients through tree root systems, and accumulation of dung of birds and animals that congregate in and under trees (Landsberg *et al.* 1990, Scholes and Archer 1997, Prober *et al.* 2002a).

Soils under trees may be better aerated than 'gap' soils (Prober *et al.* 2002b, Spooner *et al.* 2002), and contain more invertebrates such as springtails and earthworms (Chilcott *et al.* 1997, Oliver *et al.* 2006). Eldridge and Freudenberger (2005) found that water infiltration was greater under trees in fine-textured soils because there were more macropores under trees.

Several researchers have found lower soil water levels under trees than in adjacent open areas (Robertson 1985, Engle *et al.* 1987, Spooner *et al.* 2002), however many processes operate and net values are likely to vary over time. Transpiration tends to decrease water availability, while shading and the mulching effects of leaf litter limit evaporation and thus act in the opposite direction. Hydraulic lift may increase water availability near trees (Richards and Caldwell 1987, Caldwell and Richards 1989, Dawson 1993), although the benefits may be variable (Ludwig *et al.* 2003), or marginal (Moreira *et al.* 2003, Ludwig *et al.* 2004).

4.5.2 Do trees and/or shrubs influence grass production?

The answer to this question is 'yes'. Although it is not always a case of 'more trees, less grass', studies from temperate and sub-tropical regions of eastern Australia generally find that grass production is greater when tree density is low.

Trees affect the growth of understorey plants by altering the availability of resources, particularly light, water and nutrients. Although soil nutrient levels are often higher under trees (see previous section), low light levels and competition between trees and grasses for below-ground resources limit grass growth, as can accumulated tree litter and reduced moisture levels. The net effect on herbage biomass may be positive or negative (Scholes and Archer 1997, Jackson and Ash 1998). While some studies have documented increased productivity under trees (eg Weltzin and Coughenour 1990, Belsky *et al.* 1993), many others have found lower herbaceous productivity under trees and/or shrubs (Engle *et al.* 1987, Archer 1990, Scanlan and Burrows 1990), or that productivity increases when trees and shrubs are removed.

Although this question has not been directly addressed in the Northern Rivers region, it has been in south-east and central Queensland and in Poplar Box country to the west. In a field experiment in *Eucalyptus crebra* woodland near Kingaroy in Queensland, Walker *et al.* (1986b) found that grass biomass increased with decreasing tree density. Tree density in this area was initially very high (640 trees/ha). There was no significant difference in herbage biomass, however, between paddocks with 80 trees/ha, and paddocks with no trees at all. In a multi-site study in the Rockhampton area, Scanlan and Burrows (1990) found that grass yield decreased as tree basal area increased, and that this effect was greater in less fertile environments. Herbage yield also increased with decreasing tree density in *Eucalyptus populnea* woodland in southern Queensland. Although woody weeds can be a problem in this area, Walker *et al.* (1972) found shrubs reduced herb growth to a much lesser degree than trees. Finally, Harrington and Johns (1990) recorded a large increase in herbaceous biomass after clearing in *E. populnea* woodlands in western NSW. This was the case when shrubs and small trees were cleared but large trees remained (430% greater than uncleared control), and was even more pronounced when large trees were cleared as well (670% greater than uncleared control). Here, regrowth of shrubs did significantly reduce herbaceous biomass.

4.5.3 Do trees and/or shrubs influence pasture composition?

Again the answer to this question is 'yes'. Microhabitats under canopy and in open areas often support somewhat different suites of ground layer grasses and herbs. Trees and shrubs influence ground layer community composition in ecosystems around Australia (eg Walker *et al.* 1986b, Hobbs and Atkins 1991, Facelli and Temby 2002) and the world (Pieper 1990, Scholes and Archer 1997).

In temperate grassy forests and woodlands where both C3 and C4 grasses are common, winter-growing C3 species are often found under trees, while summer-active C4 grasses dominate gaps. Several studies from the Northern Tablelands document this relationship. Chilcott *et al.* (1997) found that the C3 species *Microlaena stipoides*, *Danthonia racemosa* and *Poa sieberiana* were dominant under trees in grazed open forest near Armidale, while *Aristida ramosa* and *Eragrostis* species, which use the C4 metabolic pathway, dominated spaces between trees. Gibbs *et al.* (1999), also working near Armidale, again found *Microlaena stipoides* dominant under trees, while *Aristida ramosa* was the most abundant grass in open spaces. Magcale-Macandog and Whalley (1994), working at a landscape scale, found *Microlaena stipoides* was more abundant in paddocks with >30% tree cover than in paddocks without trees across the Northern Tablelands of NSW.

Studies elsewhere in NSW and Victoria have found similar trends. Patches under trees in Box woodlands on the Western slopes of NSW were clearly distinguished through ordination from open patches (Prober *et al.* 2002a). Few native species were exclusive to either habitat, but some were more abundant under trees (eg *Dianella* ssp, *Austrodanthonia* ssp), where the C3 grass *Poa sieberiana* dominated. The C4 species *Themeda australis* dominated in gaps. C3 grasses – *Danthonia, Stipa, Microlaena* – and herbs also dominated under eucalypt canopies at Gellibrand Hill in Victoria, while *Themeda* again dominated open areas (Robertson 1985). Establishment of canopy cover reduced Blady Grass cover in a regenerating mine site near Coffs Harbour (Cummings *et al.* 2005).

Various explanations have been advanced to explain differences in species composition between under canopy and gap microhabitats. Trees may suppress dominant grasses such as *Themeda*, thus allowing more gaps for other grasses and forbs. Woody leaf litter may act as a physical barrier for large tufted grasses, favouring smaller grasses and herbs (Chilcott *et al.* 1997). Warm season grasses may not respond well to the limited light available under trees (Prober *et al.* 2002a). Higher nitrogen levels under trees (Section 4.5.1) may favour C3 grasses while C4 grasses are more competitive in the lower nutrient environment beyond tree canopies (Section 3.3).

Higher levels of fertility under trees may increase vulnerability to exotic weeds (Hobbs and Atkins 1991, Prober *et al.* 2002a). Spooner *et al.* (2002) found greater cover of exotic annual grasses under trees in the Riverina, while gaps had greater cover of perennial grasses and of herbs. However fodder under trees may also be of higher quality. C3 plants often have lower C:N ratios in their tissues than C4 plants, and this in itself may make them better forage. Even in environments where all or most grasses use the C4 pathway, microhabitats may differ in forage quality. Jackson and Ash (1998) found dry matter digestibility was greater under trees in two north Queensland woodland sites.

Trees and shrubs in pastures

- Trees and shrubs have practical, cultural, aesthetic and biodiversity values in rural landscapes. CSIRO researchers recommend at least 30% of property area should be treed, at a density of about 30 trees/ha.
- Nutrient levels are often higher under trees, and soils may be better aerated and more able to absorb water.
- Soil water levels under tree canopies are influenced by many factors and may be lower or higher than in adjacent open areas.
- Although nutrient levels are higher under trees, grass production is generally lower. Low light levels, competition between trees and grasses for below-ground resources, tree litter and reduced moisture levels limit grass growth.
- Pasture composition is often somewhat different under trees and large shrubs to that found in open areas. Winter-growing C3 grass species tend to be more abundant under trees, while summer-active C4 grasses do better in open areas.
- Because C3 grasses often have lower C:N ratios than C4 grasses, forage quality may be higher under trees, even though forage quantity is generally lower.

4.5.4 How does fire affect shrub abundance?

All elements of the fire regime – fire frequency, fire intensity, and fire season – have the potential to impact shrub abundance. Of the three, fire frequency is likely to have the greatest impact.

Fire frequency

Shrub abundance is often reduced in areas that are frequently burnt, relative to areas where burning happens less often. This trend is documented in studies both locally and elsewhere (eg Trapnell 1959, House 1995). Fires can limit woody plant density by killing seedlings of obligate seeder species before they have time to reach reproductive maturity, and those of resprouting species before they have time to reach fire tolerance (Keith 1996). Repeated burning weakens even fire-tolerant adult resprouting shrubs (Tolhurst 1996b), which may eventually die – or may at least remain suppressed, and thus vulnerable to further defoliation through grazing.

Very infrequent burning may also be associated with a reduction in the abundance of some shrub species (Watson 2005). Heat- and smoke-cued species including many wattles and peas will not regenerate in large numbers without a fire, because of dormancy mechanisms in seeds and/or fruits. Where these species are short-lived, the above-ground population will decrease in the absence of fire, although seeds will still be present in the soil, perhaps for decades (Auld 1986, Auld *et al.* 2000). Species which rely on fire to open woody fruits may be even more at risk of disappearing from unburnt habitats, as these species do not have soil-stored seed to tide them over long interfire intervals. However shrub species which are able to establish between fires may continue to increase in abundance. Examples include *Allocasuarina litoralis* in once-grassy woodland in coastal Victoria (Lunt 1998a,b) and *Bursaria spinosa* in subcoastal grassy woodland near Sydney (Watson 2005). Shrubs and small trees with rainforest affinities may fall into this category, as may some bird-dispersed species, including lantana.

Local studies which document these trends include that of Kitchin (2001), who found that Tablelands grassy forest sites burnt approximately once a decade had a higher shrub abundance than sites burnt more, or less, often. Tasker (2002) found big differences in vegetation structure between Tablelands forest sites subject to different degrees of burning: sites which were burnt regularly at 1 to 5 year intervals as part of grazing management were open and grassy, whereas plots which had been without fire for at least 15 years were dominated by small trees and shrubs. In experimental plots in Blackbutt forest north of Taree, Birk and Bridges (1989) report differences in structure between regularly burnt and unburnt plots: with burning, "the tall woody shrubs such as *Allocasuarina* and *Lantana* [were] replaced by grasses." York (1999a) measured vegetation structure on experimental plots burnt every three years for 20 years, and on plots unburnt during that time, in blackbutt forest at Bulls Ground near Port Macquarie. Cover of "tall shrubs" (100-150cm), and "very tall shrubs" (150-200cm) was considerably and significantly higher in unburnt plots.

Fire intensity

More intense fires kill more individual shrubs. This is because even fire-tolerant species are vulnerable until they grow big enough to survive a fire, and in a more intense fire, more tissue will be damaged so bigger plants will die. Morrison (1995) found that smaller stems of eight fire-tolerant small tree species were killed in low intensity fires in the lower Blue Mountains near Sydney. A later study at the same site after a high intensity fire (Morrison and Renwick 2000) found that more, and larger, stems were killed in the hotter burn.

Where control of woody plants is an issue on pastoral properties in savanna country, researchers suggest light stocking to encourage build-up of grassy fuel so that a fire of reasonably high intensity can be produced (Liedloff *et al.* 2001, Noble and Grice 2002). However more intense fires may also lead to greater germination of fire-cued shrub species such as some wattles (Shea *et al.* 1979, pers. comm. Trent Penman, Eden Burning Study, Forests NSW).

Fire and shrubs

- Many studies, including several from the Northern Rivers region, attest that frequent fire reduces the abundance of shrubs.
- Frequent burning can prevent seedlings of fire-killed shrub species from reaching maturity, and can kill seedlings of resprouting species before they reach fire tolerance. Shrubs weakened by fire may be further suppressed by grazing.
- Very infrequent burning may reduce the abundance of shrub species which rely on fire to reproduce, including many peas and wattles, although their seed may survive in the soil for decades.
- Shrubs which don't need fire to reproduce, including species with rainforest affinities and lantana, will tend to increase where fires are infrequent or have not occurred for a long time.
- Where the aim is to reduce shrub abundance, burn often. Hotter fires are likely to kill more shrubs, and regeneration may be less successful after burns in autumn than spring.
- While a single burn may initially result in germination of soil-stored seed and thus in increased shrub numbers, a second and third fire before seedlings mature should reduce the population both above and below ground.
- Where the aim is to retain or enhance abundance of fire-cued shrub species, use fire occasionally. Allow time between fires for shrubs to flower and set seed.
- To retain or enhance abundance of shrub species which can recruit between fires, exclude fire or ensure long intervals between fires.

Fire season

Season of burn may affect the extent to which shrubs are encouraged or discouraged by fire. Two ways in which this may happen are outlined below.

Firstly, season affects fire intensity through prevailing weather conditions and soil moisture. If spring fires are hotter than autumn fires, they may be associated with both greater mortality of existing shrubs, and greater germination of soil-stored seed. Williams *et al.* (2005) found much greater seedling densities after a late dry season (spring) fire in a savanna woodland near Townsville, than after an early dry season (autumn) fire – although these seedlings were mostly grasses and herbs. Previous work had shown that late dry season fires, which are hotter than early dry season fires, release a greater proportion of seed from dormancy (Williams *et al.* 2004).

Secondly, post-fire conditions may affect the ease with which resprouting species regenerate and the extent to which post-fire seedlings survive. This is the case in the semi-arid rangelands, where autumn fires have a much greater impact than spring fires (Noble 1997, Noble and Grice 2002). Locally, autumn burning may be associated with reduced establishment of fire-cued shrubs such as wattles, relative to burning in spring, particularly in areas subject to frost, where seedlings germinating after an autumn fire may be killed off over winter (Jim Morrison, pers. comm. 2005).

4.5.5 How does fire affect eucalypt recruitment?

Eucalyptus trees dominate most Northern Rivers woodland and forest vegetation types. With the possible exception of some wet forest eucalypt species (*Eucalyptus grandis, E. pilularis*) adult eucalypts in this region generally resprout after a fire.

Being long-lived, eucalypts do not need to recruit often, however some recruitment is clearly vital to replace trees lost to old age or disturbance. Where the aim is to increase tree density, McIntyre *et al.* (2002b) point out that natural regeneration is cheaper and easier than planting. Also, the genetic make-up of naturally regenerating trees is adapted to local conditions.

Surprisingly little is known about the role of fire in the recruitment of resprouting eucalypts. Eucalypt seeds are stored in the canopy; the extent to which live seed can accumulate in the soil appears to be negligible (Ashton 1979, Vlahos and Bell 1986, Read *et al.* 2000, Hill and French 2003). Recruitment in mallee eucalypts in western NSW and Victoria is limited to the period immediately after a fire (Noble 1982, Wellington and Noble 1985). Fire may enhance recruitment opportunities by reducing the competition that seedlings would otherwise experience from grasses or herbs (Noble 1980, Curtis 1990, Semple and Koen 2003), by killing some adult trees and thus creating gaps (Wellington and Noble 1985), by enhancing seedbed conditions (Clarke and Davison 2001), or by triggering sufficient seed release to cause 'predator satiation' of ants (Ashton 1979, Andersen 1988). Eucalypt recruitment may be episodic, depending on the coincidence of seed availability, gap-creating disturbance, and rainfall (Wellington and Noble 1985, Curtis 1990, Clarke 2000).

While many eucalypt seedlings die within a year or two of establishment (Noble 1982, Henry and Florence 1966, Wellington and Noble 1985, Clarke 2002), those that survive rapidly develop lignotubers which help them survive not only fire, but other disturbances such as drought and grazing (Curtis 1990, Clarke 2002). Suppressed lignotuberous seedlings can persist in the understorey for many years (Noble 1984), even in the face of regular burning (Henry and Florence 1966), though fire is capable of killing lignotuberous seedlings, particularly when it is intense (Noble 1984).

When conditions are right, lignotuberous seedlings grow through the sapling stage and join the adult population (Florence 1996). Existing adults may limit where and when this occurs (Henry and Florence 1966, Curtis 1990). Also, tree saplings within the flame zone may not be able to 'get away' to become adults if fire is frequent and/or intense (Scholes and Archer 1997). Frequent fire may limit tree recruitment by killing small diameter stems (Guinto *et al.* 1999, Williams *et al.* 1999) and returning saplings to the basal-sprouting lignotuber pool.

4.5.6 Does fire, or lack of fire, affect adult trees?

Despite the above effects, or possible effects, on recruitment, adult eucalypt basal area appears to be fairly stable under quite an extensive range of fire regimes (Watson 2005). Some studies, however, do link fluctuations in tree density to fire frequency or intensity. In the Kapalga fire experiment in the Northern Territory, intense annual fires caused a reduction in tree stems, as did a wildfire after six years of fire exclusion. Mild annual burns, however, did not affect stem survival, and at whole tree level there was little difference between treatments (Williams *et al.* 1999). Guinto *et al.* (1999) found some reduction in tree numbers with burns every 2 or 4 years in a south-east Queensland wet sclerophyll forest, as did Wellington and Noble (1985) after a single wildfire in north-western Victoria. Repeated experimental burning in autumn killed a large proportion of mallee eucalypts in western NSW Noble (1982), although this artificial situation – straw was used to enhance fuel loads – involved shorter interfire intervals than would normally occur. It may be that both frequent low intensity fire, and infrequent high intensity fire, cause some adult tree mortality.

Very long-term fire exclusion may also be associated with a decline in dominant eucalypts (Withers and Ashton 1977, Lunt 1998b), particularly in areas where shrubs, small trees and vines with rainforest affinities become well-established. Guinto *et al.* (1999) found that tree recruitment in wet sclerophyll forest in south-east Queensland, in the absence of fire, was dominated by the non-eucalypt species *Syncarpia glomulifera* and *Lophostemon confertus*. This move from eucalypt to rainforest may be accompanied by increased levels of available nitrogen in soils (Ellis and Pennington 1989).

Increased mineral nitrogen (ammonium + nitrate) may be associated with a decline in tree health, and regular burning may play a role in limiting the build-up of available nitrogen (Section 3.3). Jurskis and Turner (2002) and Turner and Lambert (2005) argue that mineral nitrogen builds up in soil in the absence of fire, to the point where eucalypts which have evolved in a low-nutrient environment may become stressed. According to the model put forward by these authors, stress affects root function, and high levels of nitrogen lead the tree to produce foliage that is particularly attractive to leaf-eating insects. High nitrogen levels, they hypothesise, also favour establishment and growth of rainforest shrubs, which produce nitrogen-rich litter which reduces C:N ratios even further. Epicormic growth after insect defoliation is also high in nutrients, which again encourages insect damage. The model proposes that, under the influence of these feedbank loops, eucalypts decline and eventually die. It is hypothesised that in the past, frequent low intensity fires kept mineral nitrogen levels low, providing stability to a system of healthy trees and grasses. This model draws on work linking rural dieback to elevated nitrogen levels (Landsberg *et al.* 1990) and on research on nutrient levels in successional sequences (Lamb 1980, Ellis and Pennington 1989) but is yet to be tested in relation to the serious problem of eucalypt dieback in Northern Rivers forests (Stone 2005). The BMAD (Bell Miner Related Dieback) Working Group aims to test elements of the model locally over the next few years.

Fire and eucalypts

- Most Northern Rivers eucalypt species resprout after fire.
- Because eucalypts are long-lived, recruitment does not need to happen very often, however some recruitment is vital. Recruitment may occur occasionally, in years when conditions are right.
- Eucalypt recruitment may be enhanced by burning, as fire creates gaps, temporarily reduces competition from grasses, and may trigger seed release.
- Young eucalypts may exist as small resprouting woody plants for many years before growing up to join the adult population. Frequent fire may limit the extent to which young eucalypts can 'get away'; saplings may be reduced to suppressed woody seedlings. Intense fires may have a similar effect.
- Despite these factors, populations of adult eucalypts appear to be fairly stable under quite a wide range of fire regimes.
- Very long-term fire exclusion or a very low fire frequency may be associated with a decline in adult eucalypts. Some researchers believe that periodic burning plays an important role in stabilising grassy eucalypt ecosystems.

4.5.7 Summary and implications

Although trees and shrubs play many valuable roles, graziers are likely to want to manage their abundance. Nutrient levels are often higher under trees, and soils may be better aerated and more able to absorb water. However overall soil water levels may be lower under trees than in open areas, and competition for light and soil resources between trees and grasses mean grass production is generally greater when tree density is low. Pasture composition under trees and some shrubs is often somewhat different to that in open areas. In temperate areas winter-growing C3 grass species such as *Microlaena stipoides* and *Poa sieberiana* are often more abundant under trees, while C4 grasses such as *Themeda* and *Aristida* favour open areas. Forage quantity may be lower under trees but quality may be higher.

Fire frequency is likely to be the primary fire-associated factor affecting shrub abundance. Frequent burning limits shrub abundance through killing seedlings of obligate seeder species before they have time to reach maturity, and those of resprouters before they reach fire tolerance. Shrubs and trees which can recruit between fires are more likely to build up numbers under infrequent burning or fire exclusion than are fire-cued species. While more intense fires will kill more shrubs, they may also stimulate more shrub seedlings to germinate. Spring fires may also have these effects, particularly if they are intense. On the other hand it has been suggested that autumn burning may limit regeneration of resprouters and discourage seedling survival to a greater extent than spring burns.

Where the aim is to decrease shrub abundance, frequent burning is recommended. As shrub seedlings generally take several years to mature, fires at short, but not yearly, intervals should accomplish this aim. Note that in areas where fire-cued shrubs such as wattles have a well-established seedbank in the soil, a single fire may initially result in an increased above-ground population of these species. However a second and third fire before these seedlings mature will reduce population numbers. Hotter fires are likely to reduce shrub populations to a greater extent than cool burns, although a hot fire may initially produce greater levels of germination of soil-stored seed. Autumn burns may be more effective than spring fires in limiting post-fire regeneration.

Where the aim is to retain or enhance populations of fire-cued shrub species, fires are important, as is the interval between them. Seedlings which germinate after an initial fire should not be burnt again until they have matured, flowered, and set seed. On the other hand, fire should not be excluded for too long, otherwise short-lived species may die off or be out-competed by species able to recruit between fires.

Where the aim is to enhance populations of shrub species which can recruit between fires, fire exclusion or long intervals between fires are recommended.

Recruitment in the resprouting eucalypts that characterise most Northern Rivers landscapes may be enhanced by fire, however frequent fire may limit the extent to which suppressed lignotuberous seedlings escape the combined effects of flames and grazing to join the adult population. Despite these influences, adult eucalypt basal area is generally stable under a wide range of fire regimes. However very frequent and/or intense fires, or fire exclusion, may affect adult eucalypt populations. Some researchers consider that regular burning may play an important role in stabilising grassy eucalypt ecosystems, and that lack of frequent low intensity fires may be a factor in eucalypt dieback.

4.6 To prevent wildfire burning out large areas

Can periodic burning in grassy woodlands and forests prevent wildfires burning out large areas? This question is important to graziers because large scale wildfires remove all feed at once, as well as causing damage to infrastructure such as fences.

The answer is that while total protection can never be guaranteed, reduced fuel loads are the only practical way to lower fire intensity. The lower the intensity of a fire, the greater the likelihood it can be contained when it starts, or controlled once it has developed.

4.6.1 Factors affecting fire control

The likelihood of controlling any particular wildfire through human intervention is inversely related to its intensity. Fire intensity is affected by the weight of combustible fuel per unit area (fuel load), the heat yield of that fuel, and the rate of forward spread of the fire front. Rate of spread is influenced by factors outside human control, particularly ambient weather conditions and topography (McAlpine 1995, Gould *et al.* 2004). Heat yield of fuel is determined by vegetation characteristics, and while there may be limited potential to manipulate this variable, for example by planting ‘fire retardant plants’ (Australian National Botanic Gardens 2003), this is unlikely to be either a cost-effective, or conservation-friendly, option in bushland. Thus the only way to realistically manage fire intensity is through regulating the amount of fuel available for a fire to consume (Simmons and Adams 1986, Morrison *et al.* 1996).

Even so, when weather conditions are extreme – high winds, hot temperatures, low humidity – even fires burning in areas where fuel loads are low can be impossible to control (Bradstock *et al.* 1998).

4.6.2 Fuel accumulation

For the purposes of this section, vegetation is fuel, and as time-since-fire progresses, fuel accumulates. Fuel dynamics relate to the relative rates of plant growth and senescence, litter deposition and breakdown (Walker 1981, Simmons and Adams 1986). When fuel loads are graphed against time-since-fire, the line takes the form of an exponential curve, rising rapidly at first, then more slowly, then reaching a plateau. The steep rise in the early post-fire years is because fuel accumulates rapidly at this time (Tolhurst 1996a) particularly after fires of relatively low intensity (Birk and Bridges 1989, Adams and Simmons 1996). Grasses grow quickly in the post-fire environment, while rates of decomposition in the litter layer are low (Fox *et al.* 1979, Raison *et al.* 1983, Woods *et al.* 1983, Neumann and Tolhurst 1991, Tolhurst 1996a).

Fuel accumulation parameters vary between vegetation types. Fuel tends to accumulate more rapidly in grassy than in shrubby sites but fuel loads in grassy vegetation may start from a lower base (because fires consume a greater proportion of available fuel), and peak at a lower level (Walker 1981, Simmons and Adams 1999, Williams *et al.* 2002, Watson 2005). In grassy woodlands near Sydney peak fuel loads are reached by about ten years post-fire, however maximum fuel loads of around 10 tonnes per hectare are considerably lower than peak loads in Sydney's shrubby sandstone woodlands, which can exceed 30 tonnes per hectare (Morrison *et al.* 1996, Watson 2005). Equilibrium fuel loads in grassy dry sclerophyll forests in Victoria reached 20 tonnes per hectare (Simmons and Adams 1999), while Birk and Bridges (1989) recorded similar levels in long-unburnt experimental plots in Blackbutt forest near Coffs Harbour. The hazard level compatible with fire control in sclerophyll vegetation of southern Australia has been calculated to lie between 8 to 15 tonnes per hectare (Gill *et al.* 1987).

While considerable fuel build-up can occur between fires even when burning occurs every few years (Birk and Bridges 1989), this practice can help maintain fuel loads at below peak levels. In Blackbutt forest near Coffs Harbour, York (1999a) found significantly less fine fuel (dry leaves, bark and twigs) on sites which had had a fire approximately every three years for 20 years than on nearby sites unburnt in that time.

Regular burning may also limit fire severity though its effect on the shrub layer. As discussed in Section 4.5.4, shrubs are likely to be less abundant where fire is relatively frequent. Shrubs provide elevated fuel which can help fire travel into tree canopies (McCarthy *et al.* 2003), so this may be less likely to occur where fire is a regular occurrence.

4.6.3 Creating a mosaic

Where the aim is to burn regularly but not annually, it is often suggested that landholders aim to create a mosaic of more and less recently burnt areas (eg Raison *et al.* 1983). England *et al.* (2004:8) suggest "exclusion of prescribed fire from sensitive areas, and use of rotational prescribed burning applied across selected areas of the landscape" to create a patchwork of areas with various degrees of fuel reduction. For example if a fire rotation of 12 years is adopted, at any time 25% of the area will contain fuels less than three years old. These authors suggest the addition of “strategically placed buffer zones that are more frequently burnt” to increase chances of fire control.

Fuel reduction should be complemented by other strategies to prevent and mitigate damage from wildfire. For example design and siting of assets, using appropriate materials, and asset maintenance can all help minimise risk.

Burning to minimise wildfire damage

- Although fuel reduction through regular burning can increase the chances that a wildfire will be able to be contained or suppressed, in extreme weather conditions this may not be possible even where fuel loads are low.
- Nevertheless, fuel reduction is the only realistic way to manage fire intensity.
- Fuel loads rise rapidly after a fire then accumulate more slowly until a plateau is reached.
- Fuel accumulation parameters vary between vegetation types. Fuel may accumulate more rapidly in grassy than in shrubby vegetation but peak loads are generally lower.
- A mosaic of more and less recently burnt areas creates a patchwork of various degrees of fuel reduction. More frequently burnt buffer zones in strategic areas can also increase the chance of fire control.
- Fuel reduction should be complemented by other strategies to prevent and mitigate wildfire damage – talk to the RFS.

4.7 To encourage native plant and animal species

4.7.1 Fire regimes for biodiversity conservation

What fire regimes might assist Northern Rivers landholders to conserve, or even enhance, the native biodiversity on their properties? This question will not be addressed in detail here, as it is the subject of another Hotspots literature review (Watson 2006). Recommended fire frequencies for Northern Rivers grassy vegetation types, from that review, are summarised below. Readers are referred the other document for supporting references and discussion.

A major theme of the fire and biodiversity review is that fire regimes, and particularly fire frequency, may need to vary across both time and space in some Northern Rivers landscapes. This is because some vegetation types, particularly those in areas with relatively fertile soils, high rainfall and warm temperatures, are able to exist in more than one fire-frequency-mediated 'state': they can be grassy and open, or more shrubby and dense. Open, grassy environments tend to be associated with moderately frequent burning, while dense vegetation is found where fire has not occurred for a long time or has only occurred occasionally (see also Sections 4.3.2 and 4.5.4 in the current document). Somewhat different suites of plant and animal species are found in each state. Some fauna species use resources from both states.

In Northern Rivers **grassy woodlands** an interfire interval range of between 3 and 10 years is recommended. Some areas should be managed on short intervals (3-6 years) while others are managed with variable intervals including some towards the top of the range. This recommendation applies to grassy woodlands between the coast and the escarpment; literature on the role of fire in Tablelands woodlands has not yet been reviewed. It is likely that somewhat longer interfire intervals would be appropriate in the cooler, drier Tablelands environment.

In Northern Rivers **dry sclerophyll shrub/grass forests** an interval range between 3 and 25 years is recommended. It is suggested that some areas (eg ridges, wide valleys, north-facing slopes) be managed on short intervals (3-6 years) to retain an open grassy understorey and to break up fuel loads to help protect refuge areas from being burnt out in wildfires. Other parts of the landscape (eg gullies, south-facing slopes) should be managed for a higher density of shrubs. Intervals between 7 and 25 years, with an emphasis on 7 to 15 years, are suggested. These figures relate to the low altitude dry sclerophyll forests which are often dominated by Spotted Gum, and to the dry sclerophyll forests of the escarpment gorges. Again, somewhat higher figures may be appropriate on the Tablelands.

In low altitude Northern Rivers **grassy wet sclerophyll forests** an interval range between 2 and 20 years is recommended. Some areas should be managed to retain an open, grassy environment: here, patchy low intensity fires at 2-5 year intervals are suggested. Other areas should be managed for a multilayered understorey: variable intervals between 5 and 20 years are suggested here. Occasional high intensity fire may be important for eucalypt regeneration.

In grassy wet sclerophyll forests on the Tablelands an interval range between 2 and 25 years is recommended. Some areas should be managed to retain an open, grassy environment: patchy low intensity fires at 2-7 year intervals are suggested. Other areas should be managed for a multilayered understorey: variable intervals between 8 and 25 years are suggested here. Occasional high intensity fire may be important for eucalypt regeneration.

Fire regimes for biodiversity conservation

- Fire frequency may need to vary across both time and space in productive Northern Rivers landscapes, as some vegetation types are able to exist in more than one fire-mediated 'state': they can be open and grassy, or more shrubby and dense.
- Open, grassy environments tend to be associated with moderately frequent burning.
- Dense vegetation is found where fire has not occurred for a long time or has only occurred occasionally.
- Somewhat different suites of plant and animal species are found in each state, so from a conservation point of view, each state is important. Some fauna species need both states.

4.7.2 Are grazing and fire interchangeable?

It is sometimes suggested that where grassy forests and woodlands are grazed, fire is not needed to conserve native plant diversity. This suggestion springs from the observation that both fire and grazing can remove built up grass biomass that limits space for the forbs and small-statured grasses that grow between tussocks of dominant grass species (Kirkpatrick and Gilfedder 1999, Johnson and Matchett 2001, Lunt and Morgan 2002).

In this section I argue that despite the above similarity, periodic fire and stock grazing are not equivalent disturbances in other regards, and are therefore likely to lead to different biodiversity outcomes over time. Differences include:

- Fire removes vegetation in a non-selective manner, while grazing animals select more palatable, and accessible, plant species.
- Fire cues or catalyses processes in the life cycle of some plant species in a way that grazing is unlikely to replicate.
- Fire is a periodic disturbance which recurs at a scale of years to decades, while grazing is often continuous. Even 'crash' grazing is likely to involve defoliation at least once or twice a year.
- Fire and grazing are probably associated with fundamentally different nutrient levels and nutrient cycling processes, which will in turn affect plant species complements.

Selectivity in vegetation removal

Many studies attest to the fact that plant species are differentially affected by grazing, and by different levels of grazing (Section 2.1). Species which are preferentially grazed are likely to decline in abundance, while unpalatable species increase. Some species which were once abundant in regularly burnt grassy woodlands have almost disappeared with grazing – the Murnong daisy (*Microseris scapigera*) in Victoria is an example (Gott 1983). Once-dominant tussock grasses such as *Themeda australis* and *Sorghum leiocladum* are very sensitive to stock grazing (Section 2.1.5), but are encouraged by fire (Section 4.4.2). In Tasmania, shoot numbers of the endangered forb *Stackhousia gunnii* generally increased after fires, but tended to decrease with grazing (Gilfedder and Kirkpatrick 1998).

Interactions between plant lifecycles and disturbance

In fire-prone ecosystems, aspects of the life histories of many plant species are cued to, or catalysed by, fire. Examples include increased post-fire flowering, a trait found in shrubs such as *Lomatia silaifolia* (Denham and Whelan 2000) and in many herbaceous species (Lunt 1994, Watson 2005); post-fire seed release, an attribute found in some eucalypts (Gill 1997) and shrubs (Bradstock and O'Connell 1988, Enright and Lamont 1989, Lamont and Connell 1996); and heat- and smoke-cued germination, a characteristic of many shrubs (Auld and O'Connell 1991, Roche *et al.* 1998, Thomas *et al.* 2003) and also of some grasses and herbs (Read *et al.* 2000, Hill and French 2003). While many grasses and herbs are not dependent on fire-related cues (even though some may respond to them when present), and thus produce seeds which should germinate readily in gaps produced by grazing animals, others may not do so.

Fires also assist seedling establishment through their effects on competition, and on nutrient and water availability. While grazing may also reduce competition from dominant grasses, it may not provide the same establishment opportunities as fire.

Williams *et al.* (2005) used cutting – which simulates grazing – to explore the differential effects of burning and defoliation without fire on seedling emergence in a savanna woodland near Townsville. Both cutting and burning produced much higher levels of seedling emergence when rain arrived than occurred in undisturbed savanna, where virtually no seedlings were found. The number of seedlings emerging was significantly greater after burning than after cutting, a difference which was also found for some individual species. Seedling survival over the next couple of years was significantly higher in burnt than cut plots, in fact virtually none of the seedlings which germinated in the cut plots survived (Williams *et al.* in preparation). From this and previous work, Williams *et al.* (2005:493) concluded that in these woodlands "multiple fire-related cues promote germination… including exposure to heat shock, smoke, enhanced nitrate levels" as well as removal of competition from the herbaceous layer.

Frequency of disturbance

Much of the literature on fire and biodiversity is concerned with the effects of fire frequency. Where fires are too frequent, many species, particularly shrubs, will be reduced in abundance and may even become locally extinct due to their inability to reach life history milestones or to survive multiple episodes of defoliation (Section 4.5.4). Where these shrub species are palatable, grazing at short intervals is likely to have similar effects. Even crash grazing would constitute a very high frequency disturbance regime relative to the lifecycle of many native shrubs.

Some herbaceous species may also be unable to complete their lifecycles when grazed. This may well apply to a greater extent under continuous grazing, which may prevent flowering, seed set, seedling establishment and/or seedling survival (Dorrough and Ash 2004). Even periodic grazing might be insufficient for herbaceous species which require longer than a year from defoliation to seed production. The orchid *Diuris punctata* may be an example (Lunt 1994).

Nutrient cycling

Differences in nutrient cycling under frequent burning and grazing have already been noted (Section 3.3). While frequent burning is associated with low levels of available nitrogen and deep-rooted C4 tussock grasses which use nitrogen efficiently, heavy grazing can increase nitrogen availability (Bromfield and Simpson 1974) and often disadvantages native C4 tussock grasses (Section 2.1.5).

Johnson and Matchett (2001) investigated the effects of fire and grazing in prairie grasslands in North America. Grazing decreased growth of grass roots, while frequent burning encouraged it. Nitrogen concentration in roots was higher in grazed areas than in ungrazed and burnt exclosures, and the C:N ratio was lower. These researchers concluded that the two disturbance processes were associated with fundamental differences in nitrogen cycling, and that this was likely to be reflected in the species complements supported under each disturbance regime. Previous work in the same ecosystem concluded that frequent fire encouraged C4 grasses which were efficient users of N, while lack of fire allowed N to build up, tipping the balance towards C3 species. Prober *et al.* (2002b) report similar dynamics in grassy Box woodlands on the Western Slopes. Woodlands which had not been degraded by heavy grazing were dominated by native tussock grasses, particularly *Themeda australis* and *Poa sieberiana* (under trees). These sites had much lower nitrate levels than more degraded sites, which were dominated either by the C3 grass taxa *Austrodanthonia* and *Austrostipa* or, in less naturally fertile areas, by *Aristida* and *Bothriochloa*, C4 taxa which do not form large tussocks. The most degraded sites had the highest levels of nitrate and were dominated by annual exotic weeds.

Other studies have also found that herbaceous exotics tend to increase with grazing pressure (McIntyre *et al.* 2003), but may decline with fire, particularly if fire helps maintain a healthy sward of *Themeda* (Lunt and Morgan 2000, Prober *et al.* 2004).

That the sum of these differences between grazing and burning can lead to different biodiversity outcomes is well illustrated in a study from Gippsland in Victoria. Lunt (1997a) compared frequently burnt but ungrazed grassy remnants with high-quality grassy forest remnants which had rarely been burnt but which were intermittently grazed. Although originating from the same species pool many years previously, areas subject to the two different management regimes differed considerably in species composition. While native species richness was higher in the unburnt quadrats, burnt quadrats had double the number of native geophytes, a category which includes native lilies and orchids. Numerous species were significantly more abundant under one regime or the other. Notably, *Themeda australis* was found in all frequently burnt sites, but was not recorded from the unburnt and grazed sites. On the other hand the C3 grasses *Danthonia geniculata, D. racemosa, Microlaena stipoides, Poa sieberiana* and *Stipa rudis* were all significantly more abundant in the grazed but unburnt remnants.

The effects of grazing relative to fire on animal species has not been explored in detail for this review. However again the biomass removal properties of grazing probably assist in providing suitable habitat for some fauna species which also favour environments generated by periodic burning (Redpath 2005). However the differential effects of fire and grazing on some habitat features, such as C4 tussock grasses, mean that the two disturbances are unlikely to be interchangeable for all native fauna species.

In conclusion, while periodic fire and livestock grazing may provide similar opportunities for persistence and recruitment for some native flora and fauna species, for other elements of the biota this will not be the case. With time, the two management regimes are likely to be associated with considerably different species complements. As Lunt (2005) points out, the evolutionary history of grassy vegetation in Australia is generally considered to have featured fire as a primary disturbance agent. While grazing by native herbivores would also have been a feature, grazing by domestic stock was not. It is not surprising, therefore, that fire and lifestock grazing do not produce the same outcomes for many native species.

Are stock grazing and fire interchangeable disturbances for biodiversity conservation?

- Both fire and grazing can remove built up grass biomass that limits space for smaller species.
- Both fire and grazing may create habitat features suitable for some native fauna species.
- BUT grazing animals are selective, while fire removes vegetation non-selectively.
- Fire cues or catalyses processes in the life cycle of some plant species in a way that grazing is unlikely to replicate.
- Fire is a periodic disturbance that occurs at a scale of years to decades, while grazing is often continuous. Even "crash" grazing is likely to involve more frequent disturbance than fire. Grazing may not allow native species enough time to complete crucial lifecycle stages.
- Fire and grazing are probably associated with different nutrient levels and cycling processes.
- As a result of these differences, over time the two management regimes are likely to be associated with considerably different species complements. Research has shown that this is indeed the case.
- So although for some native species grazing may provide an adequate substitute for fire, for many others, and for ecosystems as a whole, the answer to this question is NO.

4.7.3 Biodiversity values where burning and grazing co-exist

The above discussion of the differences between fire and grazing as disturbance agents begs the question: can biodiversity values be maintained in landscapes subject to both livestock grazing and fire?

There is evidence that high biodiversity values can be found in areas subject to both periodic fire and livestock grazing, in and near the Northern Rivers region.

York (1997, 1998, 1999b) investigated the effects of grazing and associated burning in some North Coast State Forests. This study, which focused on plants and invertebrates, found few significant differences between grazed and ungrazed sites in either the abundance, richness or composition of any group of organisms. The notable exception concerned shrubs, whose species richness was reduced in grazed areas, although on mixed sediments differences in shrub species richness were slight (Section 2.1.2 gives more details). No significant differences in richness, abundance, or species composition were identified for invertebrates overall, nor in any of 16 groups with sufficient numbers for testing (Harris *et al.* 2003,York and Tarnawski 2004; Section 2.1.4 gives more details).

Tasker (2002) compared sites which had been grazed and burnt in low-intensity 'green pick' fires at approximately 1-5 year intervals, with ungrazed sites which had remained unburnt for at least 15 years in wet sclerophyll forest on the Tablelands near Armidale. As already noted, she found big differences in vegetation structure between sites in each treatment: shrubs, vines and small trees dominated the understorey in ungrazed and unburnt sites, while grasses dominated grazed and burnt areas. However although grazed sites had a simplified structure, plant species richness was higher in the grazed and burnt sites than in the equivalent unburnt areas. Herbaceous species were particularly well-represented in the burnt and grazed plots, with many herbs found in these areas absent, or much reduced in abundance, in unburnt areas. Small mammal richness did not differ with management regime though there were big differences in species composition (Tasker and Dickman 2004). Bush rats (*Rattus fuscipes*) occurred in much greater abundance in the ungrazed and unburnt areas, and Brown Antechinus (*Antechinus stuartii*) also tended to favour these sites. However three species were caught only on the grazed and frequently burnt sites, and another mostly there – and these were rarer species, including the New Holland mouse (*Pseudomys novaehollandiae*) and the Hastings River mouse (*Pseudomys oralis*). Invertebrate community composition differed between grazed/burnt and ungrazed/unburnt areas, although there were no significant differences in the overall diversity of invertebrates caught in sticky traps placed on tree trunks. Invertebrates other than flies were significantly more abundant in grazed and burnt sites (Bickel and Tasker 2004). Stocking rates in the grazed and burnt plots in this study were low, and where grazing did occur it was not continuous (Tasker 2002).

The work of CSIRO researcher Sue McIntyre and her colleagues in south-east Queensland's Brisbane River catchment also attests to the fact that plant diversity in grazed grassy vegetation can be high in regularly burnt areas. Species richness in these woodlands, which are burnt for green pick in winter or spring, was higher at most scales in moderately grazed pastures which retained large tussock grasses than in rarely grazed areas (roadsides and TSRs) or intensively grazed patches (McIntyre *et al.* 2003). McIntyre and Martin (2001) also found high native species richness in grazed pastures in this subtropical catchment.

These examples show that regular burning combined with light to moderate levels of grazing in grassy woodlands and forests can be compatible with good outcomes for native biodiversity in the subtropical and warm temperate climates of north-eastern NSW and south-east Queensland. The combination of these disturbances may not produce such positive outcomes in cooler, drier parts of south-eastern Australia, where plants grow more slowly and thus take longer to recover from disturbance (eg Coates *et al.* 2006). The findings of these studies, together with those of the effects of stock grazing alone summarised in Section 2.1, strongly suggest that where landholders wish to manage for both biodiversity and production outcomes, grazing pressure in native vegetation will need to be limited.

Even in the subtropics some individual species decline when burning and grazing are combined (McIntyre *et al.* 2003). This can include 'keystone' species which were once ecosystem dominants: Shaw, writing in 1957, notes that *Themeda* was probably the dominant grass prior to European settlement in areas where Black Spear Grass (*Heteropogon contortus*) had since taken over, apparently due to a combination of annual burning and grazing. Shaw (1957) observed that *Themeda* still dominated frequently burnt but ungrazed environments such as railway reserves and country cemeteries. Because species can be lost when grazing and burning are combined, domestic stock should not be introduced into areas with intact and diverse native vegetation that have not been grazed historically; fire is likely to be the more appropriate disturbance agent in these areas (Lunt 2005).

Biodiversity values where fire and grazing co-exist

- Research in the Northern Rivers region and also in nearby south-east Queensland has found high biodiversity values in areas subject to both periodic fire and livestock grazing.
- Grazing pressure in areas with high native biodiversity was light to moderate and/or seasonal.
- Although the combination of these disturbances is compatible with positive outcomes in these productive subtropical areas, they may not produce such good results in cooler, drier climates where plants grow more slowly.
- Even in the subtropics some individual species decline when burning and grazing are combined.
- Domestic stock should not be introduced into areas of high quality native vegetation that have not been grazed historically.

5 MANAGEMENT IMPLICATIONS

This section draws on the information in the previous sections to present a summary of the likely effects of different management actions. Questions/topics considered are:

- How often to burn?
- What to burn?
- Season of burn
- Post-fire grazing
- Diversity in burning and grazing regimes
- Adaptive management and further research

Sometimes a preferred course of action can be identified. Often, however, there are pros and cons associated with management options, so choices and trade-offs will need to be made. Management goals, priorities and constraints will influence the course of action chosen.

5.1 How often to burn?

Frequency of burning in Northern Rivers landscapes varies widely, from almost annual burning in some places to no fire at all (Section 1.4). What features and outcomes might be associated with different fire frequencies in the relatively fertile Northern Rivers woodlands and forests commonly associated with grazing (Section 1.2)? The following descriptions assume light to moderate levels of seasonal grazing. For ease of reading, previous sections detailing supporting arguments for the points summarised below have not been referenced here[11].

Annual burning[12]

Landscapes which have been burnt annually are likely to be very open and grassy, with few shrubs and eucalypt saplings, though adult eucalypts should still be present if not logged out. Summer-active C4 grasses will dominate; some observers suggest Blady Grass rather than native tussock grasses may be favoured by this extremely frequent application of fire. Soils are likely to have low levels of organic matter particularly in the top soil layers, though grass roots may go deep; very low levels of available nitrogen, and high C:N ratios. Soil invertebrates may not do so well under this regime, and frequent loss of cover may be associated with soil crusting and erosion. Cattle will have access on an annual basis to the increased nutrient levels and productivity which follows fire – that is when rain follows burning. This regime is outside those recommended for biodiversity conservation, because of its likely negative impact on shrubs and perhaps also on some herbaceous species. While some native animals may find suitable habitat in annually burnt areas, many will not.

---

[11] It is suggested that readers wishing to follow up the points made in this section refer to the Table of Contents.

[12] In some areas it may be physically impossible to burn every year due to insufficient build-up of fuel. Any regime which involves burning as often as possible may have long-term deleterious effects because grasses will have little time to mature and produce litter, and soils will often be exposed.

Frequent, but not annual, burning

Variable interfire intervals between 2 and 5 years are likely to lead to an open grassy landscape with some eucalypt saplings and scattered shrub patches. Shrubs are more likely to be those whose germination is cued by fire than rainforest-associated species. Summer-active C4 grasses should dominate, but the mix of grass and herb species may be somewhat more diverse than under annual burning, with C3 grasses under trees particularly in more temperate areas. This regime may be the most compatible with retention of the original C4 tussock grass dominants *Themeda australis* and *Sorghum leiocladum*. Topsoils should have higher levels of organic matter than they would under annual burning, while deep-rooted grasses should ensure high levels of organic carbon in lower soil layers. Intervals between fires of 2-5 years should allow time for soil microfauna to recover, and would allow litter to accumulate to at least some degree, limiting the potential for erosion. At any one point in the landscape, cattle would have access to increased post-fire nutrient levels and productivity in some years but not others. Green pick could, however, be made available on an annual basis in some part of the landscape through careful scheduling of burns over time and space. This could also assist in spreading grazing pressure. Ample unburnt feed, though rank, would be available if post-fire rainfall failed to materialise. This fire regime – variable intervals of 2-5 years – is compatible with that suggested for maintaining the 'open, grassy' state which is an important, though by no means the only, vegetation component needed for biodiversity conservation in productive grassy North Coast vegetation types (Section 4.7.1). It should be a relatively stable state which provides habitat for a diverse ground flora and for native fauna species which use the resources available in open, grassy environments.

Regular fire, but at longer intervals

Variable intervals between, say, 5 and 15 years are likely to be associated with landscapes which have a mixture of grasses, shrubs and young eucalypts. These intervals may particularly suit fire-cued shrubs such as wattles and peas, and may also allow some rainforest-associated species to establish. Grass production is likely to be somewhat lower under this regime than under more frequent burning: the short-term boost in productivity after fire will occur infrequently, grasses will face competition from young trees and shrubs, and growth of tussock grass species may decline due to self-shading. Grass species composition may include more C3 species, particularly under trees, and particularly in more temperate areas. Traditionally dominant C4 species, such as *Themeda australis*, may decline in abundance. Soils will often be covered with litter and organic matter content in topsoils should be relatively high. Subsoils, however, may have less organic matter than where burning is frequent, as grass roots may be less extensive. Soil nitrogen levels may be higher than where burning is frequent, but are unlikely to reach the levels some fear may adversely affect eucalypt health. Erosion between fires should not be a problem however wildfires in the relatively high fuel loads retained in these landscapes may remove most cover increasing the risk that soil may be lost if heavy rain occurs soon after fire. Green pick will be available occasionally, but will not be the primary source of fodder. Variable intervals between 5 and 15 years are generally within the fire frequency thresholds compatible with biodiversity conservation in Northern Rivers grassy vegetation types. Landscapes burnt at these intervals should host a diverse shrub flora and provide habitat for many native fauna species, particularly those associated with moderately dense vegetation and flowering shrubs.

A low fire frequency or fire exclusion

Where fire is excluded altogether, or only occurs very occasionally, vegetation is likely to be quite dense, particularly in areas where soils are relatively rich, rainfall is relatively high, and temperatures are subtropical rather than temperate. These multilayered forests and woodlands are likely to have a mixture of hard and soft-leaved shrubs, with rain-forest shrubs, small trees and vines most abundant where fire has been least frequent and where soil fertility, rainfall and temperatures are high. Grasses are likely to be a limited component of these forests, while sedges and ferns may be abundant. C3 grasses are more likely than C4 grasses to survive in the low light and high nutrient environment which is predicted to characterise these forests. Litter should be abundant, as should organic matter in the topsoil, though grass roots are unlikely to be deep. Available nitrogen may occur at quite high levels, and in some areas may be associated with a decline in adult eucalypts. Erosion should not be a problem except after wildfire, when there may be risks. These landscapes are unlikely to be very useful for cattle grazing, particularly in high rainfall areas below the escarpment, as grass productivity is likely to be low. In less fertile, cooler and drier areas where shrub establishment and growth are slower, however, grazing may limit the degree to which shrubs and vines establish, producing a relatively open landscape with useable grass coverage. This fire regime – no fire, or only occasional burning – mostly falls outside the recommendations for maintenance of Northern Rivers grassy vegetation types. It will, however, be compatible with the lifecycles of a variety of native species, including some herbs, vines, and rain-forest affiliated shrubs and small trees. It will also provide habitat for native fauna with a preference for dense vegetation. In some areas, this ‘state’ may not be stable: over time it may change to rainforest.

Thus where the aim is to combine sustainable cattle grazing with biodiversity conservation, **frequent but not annual burning** appears to be the regime most likely to provide animal weight gain while still contributing substantial biodiversity value. **Regular fire at longer intervals** may also have merit, and could perhaps be practiced in some parts of the landscape to provide habitat variability for native fauna and flora. On the other hand, while **annual burning** may have advantages for cattle production short-term, this regime is likely to have relatively low value for biodiversity, and may also put long-term pasture sustainability at risk. And while **fire exclusion** may produce a landscape with value to some native plants and animals, its value for cattle grazing is likely to be low.

Burning by condition

An alternative to burning according to a set fire frequency might be to burn in response to some indicator of vegetation condition. This approach is used by managers in South African nature reserves where sustainable maintenance of fodder for grazing animals is a primary concern. For example researchers Trollope and Trollope (2004:7) recommend burning when the grass sward is “in a moribund condition”, which they define as a grass fuel load of over 4 tonnes/ha. “This criterion is intended to maintain the grass sward in a vigorous and palatable condition that will ensure adequate forage for grazing animals and provide adequate resistance to accelerated soil erosion.” This criterion, the authors point out, also ensures sufficient fuel to generate a fire hot enough to knock back unwanted shrubs. A major advantage of burning by condition rather than numbers is that it allows for variations over time and space in stocking rate and rainfall.

How often to burn?

On the basis of the information presented in the previous sections of this report, it is suggested that:

- Frequent but not annual burning, eg burning at variable intervals between 2 and 5 years, is the regime most likely to provide animal weight gain and maintain pasture condition whilst also contributing to biodiversity conservation.
- Fire at 5-15 year intervals may have less value for cattle production – eg shrubs will be thicker – but should still provide useful grazing while contributing to biodiversity conservation through enhancing habitat variability; this regime could perhaps be applied in some parts of the landscape.
- Annual burning may have advantages for cattle production in the short term but is likely to have relatively low value for native plants and animals, and may also put long-term pasture sustainability at risk.
- Fire exclusion is likely to produce a landscape with value to some native plants and animals, however its value for cattle grazing is likely to be limited as shrubs and vines build up and grass cover decreases.
- An alternative approach to burning at a particular fire frequency is to burn in response to vegetation condition eg when fuel load reaches 4 tonnes per hectare.

5.2 What to burn?

Are there grassy Northern Rivers landscapes which should not be burnt? The purpose of this section is not to discuss the need to exclude fire from rainforests – although that is indeed desirable. Nor is it to discuss the benefits and risks of burning in riparian zones – that topic, though interesting, is beyond the scope of this paper. Rather it is to consider the relationship between sward condition and burning.

In South Africa, Trollope and Trollope (2004) recommend that fire is *not* applied where the grass sward is in 'poor condition', for example where it is dominated by exotic annuals, because fire will just reinforce these patterns. The place for burning, according to these authors, is in robust stands of perennial native grasses.

Might a parallel situation exist in north-eastern NSW? Certainly the imperative for burning relates most clearly to retention of good-quality swards of native C4 tussock grasses such as *Themeda australis*. Where these species have been grazed out, the role of fire is less clear-cut. Lunt (1990) found that a single fire in a grassland in Victoria that had been grazed but not burnt for 80 years primarily benefited the exotic herbaceous species which dominated the soil seedbank.

The work of Suzanne Prober and her associates in White Box woodlands suggests, however, that fire may play a role in rehabilitating even quite degraded native pastures (Prober *et al.* 2004, 2005). Where degradation has proceeded to the point where native tussock grasses no longer form part of the sward, it may be necessary to seed them in (Prober *et al.* 2005). Where they still form a component of pasture, spring burning together with a spell from grazing may provide an opportunity for them to increase.

Where perennial exotic tussock grasses such as African Love Grass (*Eragrostic curvula*) occur amongst native tussock grasses, fire may have both benefits and risks. Enhancing the vigour of native tussock grasses may help keep exotic perennials from expanding: Lunt and Morgan (2000) found that dense stands of *Themeda australis* significantly slowed invasion by Chilean Needle Grass (*Nassella neesiana*) in a Victorian grassland. On the other hand, exotic perennials can flower rapidly and profusely after fire, and may have more extensive and permanent seedbanks than native species (Odgers 1999), characteristics which may allow some species to take advantage of the gaps created by a burn. Integrated weed management may be the only answer in these situations. One option, for small areas, could be to hand-spray exotic perennial grasses after they have resprouted post-fire but before they flower.

What to burn?

- The imperative for burning relates most clearly to retention of good-quality swards of native C4 tussock grasses.
- Where these grasses have been grazed out, the role of fire is less clear-cut. Where pastures have been unburnt but grazed for many years fire may enhance existing patterns of degradation eg through encouraging germination of exotic annual species.
- Burning together with seeding in of perennial native grasses, particularly *Themeda*, may help restore grassy native vegetation through reducing the abundance of some exotic species.
- While fire may assist in control of exotic perennial tussock grasses though encouraging native competitors, it may also provide opportunities for the exotic perennials to recruit. Caution, and an integrated weed management approach, are recommended.
- A series of fires, integrated weed management, and perhaps even seedling in of native perennial grasses may be needed where the aim is to re-establish a grassy understorey in areas where lantana and/or shrubs and vines with rainforest affinities have become well established.

Where grassy forests in productive areas have 'shrubbed up' and the aim is to restore a more grassy open understorey, a series of fires fairly close together may be necessary. Where tussock grasses are not longer part of the understorey, they may need to be seeded in. Even a series of fires is unlikely to remove lantana if it is well-established, although regular burning at 2-3 year intervals may limit its spread by encouraging seeds to germinate and killing seedlings before they reach fire tolerance. Again, integrated management may be necessarily.

5.3 Season of burn

While fire frequency is probably the most important variable to consider when deciding when to burn, there are indications that season may also influences outcomes. The research on this aspect of the fire regime is less easy to interpret, however possible relative merits of spring and autumn burns can be summarised. Again, this section draws on information presented earlier in this report.

Burning in spring

Burning in spring has been associated with relatively high levels of soil organic matter in topsoil, as this regime allows some time over winter for organic matter to be incorporated. Spring burns timed to take advantage of increasing rainfall may encourage quicker recovery of soil microfauna, and of grasses, which in turn should limit erosion risk and encourage infiltration. However shrub regeneration may be more successful after a spring burn. Spring burns may also favour natives over exotics: Prober *et al.* (2004) found two spring burns decreased the abundance of exotic grasses in a site near Young, and enhanced abundance of *Themeda.*

Burning in autumn

Autumn burns have been associated with relatively low levels of soil organic matter, even when burns were not annual. Autumn burns may leave ground more exposed over winter than spring burns. Shrub regeneration may be less successful after an autumn burn.

Queensland researchers Walker and Tothill (1992:253) point out that "Burning while pastures still retain some green material…[ie in autumn] is likely to damage still active meristematic material… Burning following the opening rains of the new growing season is the most common practice for roughage removal. These fires are usually fast and release high amounts of energy onto a plant for a short time only, and due to moisture held in plant crowns little damage is caused." South African researchers Trollope and Trollope (2004) recommend burning when the grass sward is dormant. These authors strongly suggest that fire is not used to produce out of season green pick, presumably because of the potential for damage to perennial tussock grasses. England *et al.* (2004) suggest burning when the surface soil and lower litter layer are moist so as to retain a protective layer of incompletely-combusted material. Burning soon after good spring rains may be a way to put this recommendation into practice.

Traditionally, graziers on the North Coast burnt in spring (Stubbs 2001, Tac Campbell pers. comm. 2005). Over recent years, however, more fires are being lit in autumn (Tac Campbell pers. comm. 2005). The above analysis suggests it will be important to ensure that spring burning remains a viable option for Northern Rivers landholders.

Season of burn

- While the research on season of burn is limited, there are indications that spring burns may be better for soils and perennial native tussock grasses than autumn burns.
- Shrub regeneration, however, may be less successful after autumn burning.

5.4 Post-fire grazing

While there is little research to guide decisions as to when to graze post-fire, common sense suggests that where possible, grazing should not commence immediately after fire, and should not be intense when it is resumed (Section 4.4.3). Grasses resprouting after a fire are less likely to be damaged if they have time to recover before again being defoliated. Post-fire seedlings will fare better if they have some time to establish and grow. Soils may be more able to withstand trampling if grass and litter cover have had at least some time to build up.

However research shows that enhanced nutrient levels in grasses are often highest in the first few months after fire (Section 4.1). Some trade-offs may therefore be inevitable, though decisions may not be easy. As Simpson (2000:126) points out, “Farmers are well aware of the on-farm and off-farm benefits of maintaining perennial species and ground cover. The sad reality is that when you’re battling for economic survival, short-term cash flow decisions dominate resource allocation.”

Trollope and Trollope (2004) have several suggestions as to how post-fire grazing pressure might be managed. One option is to burn relatively large areas at a time so cattle have a wide area to graze. Alternatively, a series of patch burns over several months can be used to attract animals to each area in turn and thus spread grazing pressure. Where it is possible to rest burnt areas, they suggest doing so until grass is at least 15cm high. This guideline has the advantage of being sensitive to pasture condition, rainfall and growth rates.

Other authors suggest spelling rough grazing areas until desired native grasses have flowered and set seed (Kirkpatrick and Gilfedder 1999, Nadolny *et al.* 2003), and certainly if the aim is to restore pasture condition, this will be necessary. Kemp (2000) acknowledges that this takes time and generally has a cost in short-term profitability. He suggests that the best time to try for a change in pasture composition is in a year (or ideally, in a run of years) of good rainfall as it is in these years that plant recruitment will be at its maximum. These years are also the years when feed is ample, allowing paddocks to be spelled without severe financial hazard.

Robertson (1985) and Lunt (2005) point out that heavy post-fire grazing by kangaroos can be just as problematic as grazing by cattle, and that recommendations apply equally to these animals.

Post-fire grazing

- Although again research is limited, there are reasons to suppose that grazing should not commence immediately after a fire, and should not be intense when it is resumed.
- Nutrient levels in grasses, however, are often highest in the first few months after fire. Trade-offs may therefore be inevitable.
- Suggestions for managing post-fire grazing include:
  - Burn relatively large areas at the one time so cattle can roam widely
  - Burn a series of patches to attract cattle to different areas in turn
  - Rest burnt areas till grass is at least 15 cm high.
- Where the aim is to increase the abundance of particular native pasture species, it will be necessary to spell them until they have flowered and set seed. This may best be accomplished in years of good rainfall.
- The need to manage post-fire grazing applies to native grazing animals such as kangaroos as well as to domestic stock.

5.5 Diversity in burning and grazing regimes

While some burning and grazing regimes may be superior to others for meeting a range of aims, management recommendations consistently point out that no one regime, of either fire or grazing, should be employed all the time (Leonard and Kirkpatrick 2004, Kirkpatrick *et al.* 2005). Variability is of the essence.

For example, CSIRO researchers McIntyre *et al.* (2001:28) recommend variety in both grazing and fire regimes, including "restricted heavy grazing, a range of stocking rates from light to commercial and paddock spelling at various times." A range of fire regimes could "complement schedules for fodder availability." "Although fire use is highly dependent on seasonal conditions there may be some value in allocating areas for little or no burning, irregular burning and regular burning."

Martin and Green (2002:139) also recommend a fire regime that "encompasses a range of burning histories" for on-farm areas where wildlife conservation is a goal. Particularly for those on small properties, a regional perspective is suggested; individual landholders can use fire in a way that complements prevailing regimes, and thus add to the range of habitat available across the landscape.

Barlow (1998:9) points out that "Mosaic burning in woodlands will allow refuge for wildlife to be maintained, as well as make the overall burning program easier, by doing little bits each year."

Fuhlendorf and Engle (2004:605) present a model of how grazing and fire can interact to create a 'shifting mosaic' of different patches in an Oklahoma prairie. Recent fire attracts grazing animals, which decreases the dominance of tall grasses, allowing room for forbs. Grazing also reduces biomass, making it less likely that this patch will burn next time, and so reducing the chances that that patch will again be grazed. Animals go off and graze elsewhere where fire has occurred, which allows tall grasses to recuperate. "The landscape includes local patches that have been burned and heavily grazed, dispersed within a patchwork of areas in various stages of recovery." Fuhlendorf and Engle (2004) believe this heterogeneity may be critical for conservation of many grassland species including birds.

In forests and woodlands, patchiness associated with trees, shrubs and gaps between them adds to habitat variability and may help maintain a diverse range of summer and winter grasses. Additional variability is associated with topographic features: for example vegetation tends to be thicker and more moist in gullies and on south-facing slopes than on ridges and hillsides exposed to the afternoon sun. Fire regimes can complement this natural variability so that fire is used less frequently where vegetation naturally tends to be more dense. These patterns are reinforced by fire behaviour: for example fire travels much faster up hill than down, and burns less intensely in wetter areas. Fire behaviour relative to the moisture gradients which accompany topographic features can be used to advantage when burning, complementing naturally-occurring patterns in the landscape.

Diversity in burning and grazing regimes

- While some burning and grazing regimes may be better than others for meeting particular management aims, diversity in regimes is also important.
- Diversity in disturbance regimes creates variety in habitat for native plants and animals, and so helps provide 'a place for every creature'.
- Patchiness associated with trees and the gaps between them adds to habitat diversity in forests and woodlands and may help maintain a range of summer and winter grasses.
- Topography also adds variability. Moisture gradients affect which plants grow where, and also influence fire behaviour. This variability provides opportunities to manage fire in ways that complement patterns that occur naturally in the landscape.

5.6 Adaptive management and further research

As research guidance is limited, graziers may decide to take an 'adaptive management' approach to the use of fire and post-fire grazing. This is always a good idea anyway, as what works in one situation, or at one time in climate cycles, may not work in another. Characteristics of this approach include setting clear management goals; consistent implementation of a small number of 'best bet' management regimes; documentation of management actions, fires (planned and unplanned) and grazing regimes; monitoring of outcomes, and modification of strategies and practices in the light of results (Whelan and Baker 1999).

Ideally, the many aspects of fire and grazing regimes and their effects on productivity and biodiversity would be researched through cooperative programs between graziers, universities and government or quasi-government agencies. This partnership could bring together expertise and resources, both of which are essential if studies are to generate results which can be confidently accepted. Challenges include dealing with the large number of variables which could potentially influence outcomes, ensuring adequate replication, and maintaining studies for a sufficient number of years to ensure meaningful outcomes.

Research topics could include:

- What fire and grazing regimes encourage or discourage particular native grasses in the Northern Rivers region – particularly blady grass, *Themeda*, large C4 grasses like *Sorghum* and *Capillipedium*, C3 grasses?
- Can indicators of vegetation condition which landholders can use to guide decisions as to when to burn, be identified?

Adaptive management

- As research guidance is limited, landholders may want to test out alternative management strategies.
- Adaptive management involves:
  - Clear management goals
  - Consistent implementation of 2 or 3 'best bet' management regimes
  - Documentation of management actions, fires, and grazing
  - Monitoring outcomes
  - Modification of management in the light of outcomes.
- Cooperative research programs are needed to address the many questions that remain about the effects of different grazing and burning regimes on animal production and biodiversity in the Northern Rivers region.

- Putting cattle onto burnt ground: what are the outcomes, in terms of animal weight gain, pasture composition and biodiversity, of different 'spelling' lengths and stocking rates post-fire? How do these strategies compare to ones aimed at limiting grazing pressure by free-ranging animals such as using a series of small fires to encourage animals to move around?
- Effects of season of burn. Although there has been some research elsewhere, the effects of season of burn in subtropical summer rainfall areas is not well known. Do autumn and spring fires differ in their effects on pasture composition, ground layer diversity, soil invertebrates? Are weeds reduced or enhanced to a different degree depending on season of burn? Do shrubs germinate more readily after autumn or spring fires? Do post-fire seedlings survive better over summer or winter? Are resprouting shrubs, particularly lantana, more likely to die after an autumn or a spring fire?

This review has been compiled for the Hotspots Fire Project, with input from a range of stakeholders. Further input is being sought in the form of comments on this draft. The information in this document reflects the author's understanding at the time of release, and is not definitive. As comments come in (in the short term) and as research advances (in the longer term) it is likely that some recommendations will change.

References

Abbott, I., van Heurck, P. and Wong, L. (1984) Responses to long-term fire exclusion: physical, chemical and faunal features of litter and soil in a Western Australian forest. *Australian Forestry* **47**, 237-242.

Adams, M.A., Iser, J., Keleher, A.D. and Cheal, D.C. (1994) Nitrogen and phosphorus availabililty and the role of fire in heathlands at Wilsons Promontory. *Australian Journal of Botany* **42**, 269-281.

Adams, R. and Simmons, D. (1996) The impact of fire intensity on litter loads and understorey floristics in an urban fringe dry sclerophyll forest and implications for management. Pp. 21-35 in *Fire and Biodiversity: the Effects and Effectiveness of Fire Management* (ed. by J.R. Merrick). Proceedings of conference held in Melbourne on 8-9 October 1994. Commonwealth Department of Environment, Sport and Territories, Canberra.

Andersen, A.N. (1988) Immediate and longer-term effects of fire on seed predation by ants in sclerophyllous vegetation in south-eastern Australia. *Australian Journal of Ecology* **13**, 285-293.

Andersen, A.N., Braithwaite, R.W., Cook, G.D., Corbett, L.K., Williams, R.J., Douglas, M.M., Gill, A.M., Setterfield, S.A. and Muller, W.J. (1998) Fire research for conservation management in tropical savannas: introducing the Kapalga fire experiment. *Australian Journal of Ecology* **23**, 95-110.

Andrew, M.H. (1986) Use of fire for spelling monsoon tallgrass pasture grazed by cattle. *Tropical Grasslands* **20**, 69-78.

Aranibar, J.N., Macko, S.A., Anderson, I.C., Potgieter, A.L.F., Sowry, R. and Shugart, H.H. (2003) Nutrient cycling responses to fire frequency in the Kruger National Park (South Africa) as indicated by stable isotope analysis. *Isotopes Environment and Health Studies* **39**, 141-158.

Archer, S. (1990) Development and stability of grass/woody mosaics in a subtropical savanna parkland, Texas, U.S.A. *Journal of Biogeography* **17**, 453-462.

Archibald, S. and Bond, W.J. (2004) Grazer movements: spatial and temporal responses to burning in a tall-grass African savanna. *International Journal of Wildland Fire* **13**, 377-385.

Ash, A.J., Prinsen, J.H., Myles, D.J. and Hendricksen, R.E. (1982) Short-term effects of burning native pasture in spring on herbage and animal production in south-east Queensland. *Proceedings of the Australian Society of Animal Production* **14**, 377-380.

Ashton, D.H. (1979) Seed harvesting by ants in forests of *Eucalyptus regnans* F. Muell. in central Victoria. *Australian Journal of Ecology* **4**, 265-277.

Atkinson, G. (1984) Erosion damage following bushfires. *Journal of Soil Conservation of New South Wales* **40**, 4-9.

Auld, T.D. (1986) Population dynamics of the shrub *Acacia suaveolens* (Sm.) Willd.: dispersal and the dynamics of the soil seed-bank. *Australian Journal of Ecology* **11**, 235-254.

Auld, T.D. and O'Connell, M.A. (1991) Predicting patterns of post-fire germination in 35 eastern Australian Fabaceae. *Australian Journal of Ecology* **16**, 53-70.

Auld, T.D., Keith, D.A. and Bradstock, R.A. (2000) Patterns in longevity of soil seedbanks in fire-prone communities of south-eastern Australia. *Australian Journal of Botany* **48**, 539-548.

Australian National Botanic Gardens (2003) *Fire, gardens and fire retardant plants - a bibliography*. On line at http://www.anbg.gov.au/bibliography/fire-plants.html. Last amended 21 March 2003. Accessed 28 April 2005.

Barlow, T. (1998) *Grassy Guidelines: How to Manage Native Grasslands and Grassy Woodlands on your Property*. Trust for Nature, Melbourne.

Belsky, A.J., Mwonga, S.M., Amundson, R.G., Duxbury, J.M. and Ali, A.R. (1993) Comparative effects of isolated trees on their undercanopy environments in high- and low-rainfall savannas. *Journal of Applied Ecology* **30**, 143-155.

Bennett, L.T. (1994) The expansion of *Leptospermum laevigatum* on the Yanakie Isthmus, Wilson's Promontory, under changes in the burning and grazing regimes. *Australian Journal of Botany* **42**, 555-564.

Benson, D.H. (1992) The natural vegetation of the Penrith 1:100 000 map sheet. *Cunninghamia* **2**, 541-596.

Benson, J.S. and Redpath, P.A. (1997) The nature of pre-European native vegetation in south-eastern Australia: a critique of Ryan, D.G., Ryan, J.R. and Starr, B.J. (1995) *The Australian Landscape - Observations of Explorers and Early Settlers*. *Cunninghamia* **5**, 285-328.

Bickel, D.J. and Tasker, E.M. (2004) Tree trunk invertebrates in Australian forests: conserving unknown species and complex processes. Pp. 888-898 in *The Conservation of Australia's Forest Fauna (2nd edition)* (ed. by D. Lunney). Royal Zoological Society of New South Wales, Mosman, NSW.

Birk, E.M. and Bridges, R.G. (1989) Recurrent fires and fuel accumulation in even-aged Blackbutt (*Eucalyptus pilularis*) forests. *Forest Ecology and Management* **29**, 59-79.

Bond, W.J. (1997) Fire. Pp. 421-446 in *Vegetation of Southern Africa* (ed. by R.M. Cowling, D.M. Richardson and S.M. Pierce). Cambridge University Press, Cambridge.

Bowman, D.M.J.S. and Fensham, R.J. (1991) Response of a monsoon forest-savanna boundary to fire protection, Weipa, northern Australia. *Australian Journal of Ecology* **16**, 111-118.

Bradstock, R.A. and Gill, A.M. (2001) Living with fire and biodiversity at the urban edge: in search of a sustainable solution to the human protection problem in southern Australia. *Journal of Mediterranean Ecology* **2**, 179-195.

Bradstock, R.A. and O'Connell, M.A. (1988) Demography of woody plants in relation to fire: *Banksia ericifolia* L.f. and *Petrophile pulchella* (Schrad) R.Br. *Australian Journal of Ecology* **13**, 505-518.

Bradstock, R.A., Gill, A.M., Kenny, B.J. and Scott, J. (1998) Bushfire risk at the urban interface estimated from historical weather records: consequences for the use of prescribed fire in the Sydney region of south-eastern Australia. *Journal of Environmental Management* **52**, 259-271.

Bromfield, S.M. and Simpson, J.R. (1974) Effects of management on soil fertility under pasture. 2. Changes in nutrient availability. *Australian Journal of Experimental Agriculture and Animal Husbandry* **14**, 479-486.

BRS (Bureau of Rural Sciences) (nd) *Natural Resource Management Regions: Northern Rivers*. Australian Government Bureau of Rural Sciences. Available on web at http://www.daff.gov.au/corporate_docs/publications/pdf/rural_science/lms/nthriv.pdf. Accessed 20 April 2006., Canberra.

Bureau of Meteorology (2005) *What is the weather usually like? Climate averages for New South Wales and ACT sites*. On line at http://www.bom.gov.au/climate/averages/tables/ca_nsw_names.shtml. Accessed July 2005.

Caldwell, M.M. and Richards, J.H. (1989) Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. *Oecologia* **79**, 1-5.

Chilcott, C., Reid, N.C.H. and King, K. (1997) Impact of trees on the diversity of pasture species and soil biota in grazed landscapes on the Northern Tablelands, NSW. Pp. 378-386 in *Conservation Outside Nature Reserves* (ed. by P. Hale and D. Lamb). Centre for Conservation Biology, University of Queensland, Brisbane.

Clarke, P.J. (2000) Plant population processes in temperate woodlands of eastern Australia - premises for management. Pp. 248-270 in *Temperate Eucalypt Woodlands in Australia: Biology, Conservation, Management and Restoration* (ed. by R.J. Hobbs and C.J. Yates). Surrey Beatty and Sons, Chipping Norton, NSW.

Clarke, P.J. (2002) Experiments on tree and shrub establishment in temperate grassy woodlands: seedling survival. *Austral Ecology* **27**, 606-615.

Clarke, P.J. (2003) Composition of grazed and cleared temperate grassy woodlands in eastern Australia: patterns in space and inferences in time. *Journal of Vegetation Science* **14**, 5-14.

Clarke, P.J. and Davison, E.A. (2001) Experiments on the mechanism of tree and shrub establishment in temperate grassy woodlands: seedling emergence. *Austral Ecology* **26**, 400-412.

Clarke, S. (2003) *The Effect of Fire and Grazing on Cumberland Plain Woodlands*. Master of Science (Research) thesis, University of Wollongong.

Cluff, D. and Semple, B. (1994) Natural regeneration - in "Mother Nature's" own time. *Australian Journal of Soil and Water Conservation* **7**, 28-33.

Coates, F., Lunt, I.D. and Tremblay, R.L. (2006) Effects of disturbance on population dynamics of the threatened orchid *Prasophyllum correctum* D.L. Jones and implications for grassland management in south-eastern Australia. *Biological Conservation* **129**, 59-69.

Cummings, J., Reid, N., Davies, I. and Grant, C. (2005) Adaptive restoration of sand-mined areas for biological conservation. *Journal of Applied Ecology* **42**, 160-170.

Curtis, D. (1990) Natural regeneration of eucalypts in the New England region. Pp. 7-16 in *'Sowing the Seeds': Direct Seeding and Natural Regeneration Conference* . Greening Australia, Canberra.

Dawson, T.E. (1993) Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. *Oecologia* **95**, 565-574.

DeBano, L.F. (2000) The role of fire and soil heating on water repellancy in wildland environments: a review. *Journal of Hydrology* **231-232**, 195-206.

Denham, A.J. and Whelan, R.J. (2000) Reproductive ecology and breeding system of *Lomatia silaifolia* (Proteaceae) following a fire. *Australian Journal of Botany* **48** , 261-269.

Derner, J.D., Briske, D.D. and Boutton, T.W. (1997) Does grazing mediate soil carbon and nitrogen accumulation beneath C4, perennial grasses along an environmental gradient? *Plant and Soil* **191**, 147-156.

Dorrough, J. and Ash, J. (2004) The impact of livestock grazing on the persistence of a perennial forb in a temperate Australian grassland. *Pacific Conservation Biology* **9**, 302-307.

DPI (Department of Primary Industries NSW) (2002) *Soil organic matter*. Available on the internet at http://www.agric.nsw.gov.au/reader/soil-types-structure/ss593-soil-organic-matter.htm. Accessed 16 March 2006,

Dragovich, D. and Morris, R. (2002) Fire intensity, slopewash and bio-transfer of sediment in eucalypt forest, Australia. *Earth Surface Processes and Landforms* **27**, 1309-1319.

DTRS (Department of Transport and Regional Services) (2005) *A Regional Profile. Northern Rivers and North Coast NSW Region*. Australian Government Department of Transport and Regional Services, Canberra. Available on web at http://www.sustainableregions.gov.au/downloads/sr_nsw_nrnc_profile.pdf. Accessed 16 March 2006.

Earl, J.M. and Jones, C.E. (1996) The need for a new approach to grazing management - is cell grazing the answer? *The Rangeland Journal* **18**, 327-350.

Edwards, A., Kennett, R., Price, O., Russell-Smith, J., Spiers, G. and Woinarski, J. (2003) Monitoring the impacts of fire regimes on vegetation in northern Australia: an example from Kakadu National Park. *International Journal of Wildland Fire* **12**, 427-440.

Eldridge, D.J. and Freudenberger, D. (2005) Ecosystem wicks: woodland trees enhance water infiltration in a fragmented agricultural landscape in eastern Australia. *Austral Ecology* **30**, 336-347.

Ellis, R.C. and Pennington, P.I. (1989) Nitrification in soils of secondary vegetational successions from *Eucalptus* forest and grassland to cool temperate rainforest in Tasmania. *Plant and Soil* **115**, 59-73.

England, J., Doherty, M., Keith, H. and Raison, J. (2004) *Ecological Effects of Burning in ACT Vegetation Communities*. Report No. 7, ACT Bushfire Projects. ACT Department of Urban Services, Canberra. On line at http://www.urbanservices.act.gov.au/stateofknowledgesummaries.html. Accessed 23 June 2005.

Engle, D.M., Stritzke, J.F. and Claypool, P.L. (1987) Herbage standing crop around eastern redcedar trees. *Journal of Range Management* **40**, 237-239.

Enright, N.J. and Lamont, B.B. (1989) Seed banks, fire season, safe sites and seedling recruitment in five co-occurring *Banksia* species. *Journal of Ecology* **77**, 1111-1122.

Facelli, J.M. and Temby, A.M. (2002) Multiple effects of shrubs on annual plant communities in arid lands of South Australia. *Austral Ecology* **27**, 422-432.

Fensham, R.J. (1998) The grassy vegetation of the Darling Downs, south-eastern Queensland, Australia. Floristics and grazing effects. *Biological Conservation* **84**, 301-310.

Florence, R.G. (1996) *Ecology and Silviculture of Eucalypt Forests*. CSIRO Publishing, Collingwood.

Fox, B.J., Fox, M.D. and McKay, G.M. (1979) Litter accumulation after fire in a eucalypt forest. *Australian Journal of Botany* **27**, 157-165.

Fuhlendorf, S.D. and Engle, D.M. (2004) Application of the fire-grazing interaction to restore a shifting mosaic on tallgrass prairie. *Journal of Applied Ecology* **41**, 604-614.

Fuls, E.R. (1992) Ecosystem modification created by patch-overgrazing in semi-arid grassland. *Journal of Arid Environments* **23**, 59-69.

Fynn, R.W.S., Haynes, R.J. and O'Connor, T.G. (2003) Burning causes long-term changes in soil organic matter content of a South African grassland. *Soil Biology and Biochemistry* **35**, 677-687.

Fynn, R.W.S., Morris, C.D. and Edwards, T.J. (2005) Long-term compositional responses of a South African mesic grassland to burning and mowing. *Applied Vegetation Science* **8**, 5-12 .

Gibbs, L., Reid, N. and Whalley, R.D.B. (1999) Relationships between tree cover and grass dominance in a grazed temperate stringybark (*Eucalyptus laevopinea*) open-forest. *Australian Journal of Botany* **47**, 49-60.

Gilfedder, L. and Kirkpatrick, J.B. (1998) Distribution, disturbance tolerance and conservation of *Stackhousia gunnii* in Tasmania. *Australian Journal of Botany* **46**, 1-13.

Gill, A.M. (1981) Adaptive responses of Australian vascular plant species to fires. Pp. 243-272 in *Fire and the Australian Biota* (ed. by A.M. Gill, R.H. Groves and I.R. Noble). Australian Academy of Science, Canberra.

Gill, A.M. (1997) Eucalypts and fires: interdependent or independent? Pp. 151-167 in *Eucalypt Ecology: Individuals to Ecosystems* (ed. by J. Williams and J. Woinarski). Cambridge University Press, Cambridge.

Gill, A.M., Christian, K., Moore, P. and Forrester, R. (1987) Bushfire incidence, fire hazard and fuel reduction burning. *Australian Journal of Ecology* **12**, 299-306.

Gilmour, D.A. (1968) Hydrological investigations of soil and vegetation types in the lower Cotter catchment. *Australian Forestry* **32**, 243-256.

Gleadow, R.M. and Ashton, D.H. (1981) Invasion by *Pittosporum undulatum* of the forests of central Victoria. I. Invasion patterns and plant morphology. *Australian Journal of Botany* **29**, 705-720.

Good, R.B. (1973) A preliminary assessment of erosion following wildfires in Kosciusko National Park, N.S.W. in 1973. *Journal of Soil Conservation of NSW* **29**, 191-199.

Gott, B. (1983) Murnong - *Microseris scapigera*: a study of a staple food of Victorian Aborigines. *Australian Aboriginal Studies* **1983/2**, 2-18.

Gould, J.S., McCaw, W.L. and Cheney, N.P. (2004) *Project Vesta - findings, extension and validation for south eastern Australia eucalypt forests*. Paper presented at the Bushfire 2004 Conference, Adelaide, May 2004. http://www.environment.sa.gov.au/biodiversity/bushfire_proceedings.html. Accessed 20 April 2006.

Guinto, D.F., House, A.P.N., Xu, Z.H. and Saffigna, P.G. (1998) *Changes in soil chemical properties and forest floor nutrients under repeated prescribed burning in eucalypt forests of south-east Queensland*. Queensland Forestry Research Institute. Research Note No. 49, Brisbane.

Guinto, D.F., House, A.P.N., Xu, Z.H. and Saffigna, P.G. (1999) Impacts of repeated fuel reduction burning on tree growth, mortality and recruitment in mixed species eucalypt forests of southeast Queensland, Australia. *Forest Ecology and Management* **115**, 13-27.

Guinto, D.F., Xu, Z.H., House, A.P.N. and Saffigna, P.G. (2001) Soil chemical properties and forest floor nutrients under repeated prescribed-burning in eucalypt forests of south-east Queensland, Australia. *New Zealand Journal of Forestry Science* **31**, 170-187.

Guinto, D.F., Xu, Z.H., House, A.P.N. and Saffigna, P.G. (2002) Influence of fuel reduction burning and fertilisation on the growth and nutrition of eucalypt seedlings. *Journal of Tropical Forest Science* **14**, 536-546.

Harrington, G.N. and Johns, G.G. (1990) Herbaceous biomass in a *Eucalyptus* savanna woodland after removing trees and/or shrubs. *Journal of Applied Ecology* **27**, 775-787.

Harris, R., York, A. and Beattie, A.J. (2003) Impacts of grazing and burning on spider assemblages in dry eucalypt forests of north-eastern New South Wales, Australia. *Austral Ecology* **28**, 526-538.

Hart, S.C., DeLuca, T.H., Newman, G.S., MacKenzie, M.D. and Boyle, S.I. (2005) Post-fire vegetative dynamics as drivers of microbial community structure and function in forest soils. *Forest Ecology and Management* **220**, 166-184.

Henderson, M.K. and Keith, D.A. (2002) Correlation of burning and grazing indicators with composition of woody understorey flora of dells in a temperate eucalypt forest. *Austral Ecology* **27**, 121-131.

Henry, N.B. and Florence, R.G. (1966) Establishment and development of regeneration in Spotted Gum - Ironbark forests. *Australian Forestry* **30**, 304-316.

Hill, S.J. and French, K. (2003) Response of the soil seed-bank of Cumberland Plain Woodland to heating. *Austral Ecology* **28**, 14-22.

Hill, S.J. and French, K. (2004) Potential impacts of fire and grazing in an endangered ecological community: plant composition and shrub and eucalypt regeneration in Cumberland Plain Woodland. *Australian Journal of Botany* **52**, 23-29.

Hobbs, R.J. and Atkins, L. (1991) Interactions between annuals and woody perennials in a Western Australian nature reserve. *Journal of Vegetation Science* **2**, 643-654.

House, A. (1995) Fire ecology research in Queensland native forests - current status and new directions. Pp. 86-97 in *Working Papers - Sixth Queensland Fire Research Workshop, 8-10 March 1995, Bargara, Queensland* . Land Use Study Centre, University of Southern Queensland, Toowoomba.

Jackson, J. and Ash, A.J. (1998) Tree-grass relationships in open eucalypt woodlands of northeastern Australia: influence of trees on pasture productivity, forage quality and species distribution. *Agroforestry Systems* **40**, 159-176.

Jackson, J. and Ash, A.J. (2001) The role of trees in enhancing soil nutrient availability for native perennial grasses in open eucalypt woodlands of north-east Queensland. *Australian Journal of Agricultural Research* **52**, 377-386.

Jarman, P.J., Johnson, C.N., Southwell, C.J. and Stuart-Dick, R. (1987) Macropod studies at Wallaby Creek. I. The area and animals. *Australian Wildlife Research* **14**, 1-14.

Johnson, D. (2005) *A farmer's perspective on fire*. Paper presented at fire management workshop organised by West of the Ranges Landcare Inc (WORLI), 8 October 2005, Johnson, L.C. and Matchett, J.R. (2001) Fire and grazing regulate belowground processes in tallgrass prairie. *Ecology* **82**, 3377-3389.

Johnston, W.H. (2000) Perennial native grasses - the quiet achievers. Pp. 133-141 in *Balancing Conservation and Production in Grassy Landscapes* (ed. by T. Barlow and R. Thorburn). Proceedings of conference held in Clare, South Australia on 19-21 August 1999. Environment Australia, Canberra. On line at http://www.deh.gov.au/land/publications/grasscon/. Accessed 8 July 2005.

Jurskis, V. and Turner, J. (2002) Eucalypt dieback in eastern Australia: a simple model. *Australian Forestry* **65**, 81-92.

Keith, D. (1996) Fire-driven extinction of plant populations: a synthesis of theory and review of evidence from Australian vegetation. *Proceedings of the Linnean Society of New South Wales* **116**, 37-78.

Kelly, C. (2004) *The Effects of Fire Frequency on the Understorey of a Subalpine Snow Gum Forest*. Honours thesis, Australian National University,

Kemp, D.R. (2000) Managing grassland composition with grazing. Pp. 145-152 in *Balancing Conservation and Production in Grassy Landscapes* (ed. by T. Barlow and R. Thorburn). Proceedings of conference held in Clare, South Australia on 19-21 August 1999. Environment Australia, Canberra. On line at http://www.deh.gov.au/land/publications/grasscon/. Accessed 8 July 2005.

Kirkpatrick, J.B. and Gilfedder, L.A. (1999) *Tasmanian Bushcare Toolkit*. Tasmanian Department of Primary Industries, Water and Environment, Hobart.

Kirkpatrick, J.B., Gilfedder, L., Bridle, K. and Zacharek, A. (2005) The positive and negative conservation impacts of sheep grazing and other disturbances on the vascular plant species and vegetation of lowland subhumid Tasmania. *Ecological Management and Restoration* **6**, 51-60.

Kitchin, M.B. (2001) *Fire Ecology and Fire Management for the Conservation of Plant Species and Vegetation Communities in a National Park in Northern NSW, Australia*. PhD thesis, University of New England.

Lamb, D. (1980) Soil nitrogen mineralisation in a secondary rainforest succession. *Oecologia* **47**, 257-263.

Lamont, B.B. and Connell, S.W. (1996) Biogeography of *Banksia* in southwestern Australia. *Journal of Biogeography* **23**, 295-309.

Landsberg, J., Morse, J. and Khanna, P. (1990) Tree dieback and insect dynamics in remnants of native woodlands on farms. *Proceedings of the Ecological Society of Australia* **16**, 149-165.

Landsberg, J., James, C.D., Maconochie, J., Nicholls, A.O., Stol, J. and Tynan, R. (2002) Scale-related effects of grazing on native plant communities in an arid rangeland region of South Australia. *Journal of Applied Ecology* **39**, 427-444.

Leigh, J.H. and Holgate, M.D. (1979) The responses of the understorey of forests and woodlands of the Southern Tablelands to grazing and burning. *Australian Journal of Ecology* **4**, 25-45.

Leigh, J.H., Wood, D.H., Slee, A.V. and Holgate, M.D. (1991) The effects of burning and simulated grazing on productivity, forage quality, mortality and flowering of eight subalpine herbs in Kosciusko National Park. *Australian Journal of Botany* **39**, 97-118.

Leonard, S.W.J. and Kirkpatrick, J.B. (2004) Effects of grazing management and environmental factors on native grassland and grassy woodland, Northern Midlands, Tasmania. *Australian Journal of Botany* **52**, 529-542.

Liedloff, A.C., Coughenour, M.B., Ludwig, J.A. and Dyer, R. (2001) Modelling the trade-off between fire and grazing in a tropical savanna landscape, northern Australia. *Environment International* **27**, 173-180.

Lodge, G.M. and Whalley, R.D.B. (1985) The manipulation of species composition of natural pastures by grazing management on the Northern Slopes of New South Wales. *Australian Rangeland Journal* **7**, 6-16.

Lodge, G.M., Murphy, S.R. and Johnson, I.R. (2001) *Soil water balance modelling highlights limitations for pasture production in northern NSW*. Paper presented at the Australian Agronomy Conference, 2001. http://www.regional.org.au/au/asa/2001/2/b/lodge.htm. Accessed 11 July 2005.

Ludwig, F., Dawson, T.E., Kroon, H., Berendse, F. and Prins, H.H.T. (2003) Hydraulic lift in *Acacia tortilis* trees on an East African savanna. *Oecologia* **134**, 293-300.

Ludwig, F., Dawson, T.E., Prins, H.H.T., Berendse, F. and de Kroon, H. (2004) Below-ground competition between trees and grasses may overwhelm the facilitative effects of hydraulic lift. *Ecology Letters* **7**, 623-631.

Lunt, I.D. (1990) Impact of an autumn fire on a long-grazed *Themeda triandra* (Kangaroo Grass) grassland: implications for management of invaded, remnant vegetations. *Victorian Naturalist* **107**, 45-51.

Lunt, I.D. (1994) Variation in flower production of nine grassland species with time since fire, and implications for grassland management and restoration. *Pacific Conservation Biology* **1**, 359-366.

Lunt, I.D. (1997a) Effects of long-term vegetation management on remnant grassy forests and anthropogenic native grasslands in south-eastern Australia. *Biological Conservation* **81**, 287-297.

Lunt, I.D. (1997b) Tree densities last century on the lowland Gippsland plain, Victoria. *Australian Geographical Studies* **35**, 342-348.

Lunt, I.D. (1998a) Two hundred years of land use and vegetation change in a remnant coastal woodland in southern Australia. *Australian Journal of Botany* **46**, 629-647.

Lunt, I.D. (1998b) *Allocasuarina* (Casuarinaceae) invasion of an unburnt coastal woodland at Ocean Grove, Victoria: structural changes, 1971-1996. *Australian Journal of Botany* **46**, 649-656.

Lunt, I.D. (2005) *Effects of Stock Grazing on Biodiversity Values in Temperate Native Grasslands and Grassy Woodlands in SE Australia: a Literature Review. Technical Report 18*. Environment ACT, Lyneham, ACT.

Lunt, I.D. and Morgan, J.W. (1999a) Vegetation changes after 10 years of grazing exclusion and intermittent burning in a *Themeda triandra* (Poaceae) grassland reserve in south-eastern Australia. *Australian Journal of Botany* **47**, 537-552.

Lunt, I.D. and Morgan, J.W. (1999b) Effect of fire frequency on plant composition at the Laverton North Grassland Reserve, Victoria. *Victorian Naturalist* **116**, 84-90.

Lunt, I.D. and Morgan, J.W. (2000) Can competition from *Themeda triandra* inhibit invasion by the perennial exotic grass *Nassella neesiana* in native grasslands? *Plant Protection Quarterly* **15**, 92-94.

Lunt, I.D. and Morgan, J.W. (2002) The role of fire regimes in temperate lowland grasslands of southeastern Australia. Pp. 177-196 in *Flammable Australia: the Fire Regimes and Biodiversity of a Continent* (ed. by R.A. Bradstock, J.E. Williams and A.M. Gill). Cambridge University Press, Cambridge.

Madany, M.H. and West, N.E. (1983) Livestock grazing-fire regime interactions within montane forests of Zion National Park, Utah. *Ecology* **64**, 661-667.

Magcale-Macandog, D.B. and Whalley, R.D.B. (1994) Factors affecting the distribution and abundance of *Microlaena stipoides* (Labill.) R.Br. on the Northern Tablelands of New South Wales. *Rangeland Journal* **16**, 26-38.

Martin, T.G. and Green, J.L. (2002) Wildlife and core conservation areas. Pp. 111-142 in *Managing and Conserving Grassy Woodlands* (ed. by S. McIntyre, J.G. McIvor and K.M. Heard). CSIRO Publishing, Collingwood, Victoria.

McAlpine, R.S. (1995) Testing the effect of fuel consumption on fire spread rate. *International Journal of Wildland Fire* **5**, 143-152.

McCarthy, G.J., Tolhurst, K.G. and Chatto, K. (2003) *Overall Fuel Hazard Guide. Third edition.* Department of Sustainability and Environment, Victoria, Melbourne.

McGowen, I. (2003) *Pasture recovery after bushfires*. Available on NSW Department of Primary Industries website at http://www.agric.nsw.gov.au/reader/past-management/p237.htm. Accessed 20 April 2006.

McIntosh, P.D., Laffan, M.D. and Hewitt, A.E. (2005) The role of fire and nutrient loss in the genesis of the forest soils of Tasmania and southern New Zealand. *Forest Ecology and Management* **220**, 185-215.

McIntyre, S. (2002) Trees. Pp. 79-110 in *Managing and Conserving Grassy Woodlands* (ed. by S. McIntyre, J.G. McIvor and K.M. Heard). CSIRO Publishing, Collingwood, Victoria.

McIntyre, S. and Martin, T.G. (2001) Biophysical and human influences on plant species richness in grasslands: comparing variegated landscapes in subtropical and temperate regions. *Austral Ecology* **26**, 233-245.

McIntyre, S. and Tongway, D. (2005) Grassland structure in native pastures: links to soil surface condition. *Ecological Management and Restoration* **6**, 43-50.

McIntyre, S., Lavorel, S. and Tremont, R.M. (1995) Plant life-history attributes: their relationship to disturbance response in herbaceous vegetation. *Journal of Ecology* **83**, 31-44.

McIntyre, S., McIvor, J.G. and MacLeod, N.D. (2000) Principles for sustainable grazing in eucalypt woodlands: landscape-scale indicators and the search for thresholds. Pp. 92-100 in *Management for Sustainable Ecosystems* (ed. by P. Hale, A. Petrie, D. Moloney and P. Sattler). Centre for Conservation Biology, University of Queensland, Brisbane.

McIntyre, S., McIvor, J. and Macleod, N. (2001) New grazing approach is vital for sustainability. *Farming Ahead* **No. 120**, 27-28. Available on line at http://www.cse.csiro.au/research/documents/FAnewgrazing.pdf. Accessed 20 April 2006 .

McIntyre, S., McIvor, J.G. and Heard, K.M. (2002a) *Managing and Conserving Grassy Woodlands*. CSIRO Publishing, Collingwood, Victoria.

McIntyre, S., McIvor, J. and Macleod, N. (2002b) Maintaining trees enhances grazing potential. *Farming Ahead* **No. 121**, 47-48. Available on line at http://www.cse.csiro.au/research/documents/FAgrazingpotential.pdf. Accessed 20 April 2006.

McIntyre, S., Heard, K.M. and Martin, T.G. (2003) The relative importance of cattle grazing in subtropical grasslands: does it reduce or enhance plant biodiversity? *Journal of Applied Ecology* **40**, 445-457.

McIvor, J.G. (2002) Soils. Pp. 41-60 in *Managing and Conserving Grassy Woodlands* (ed. by S. McIntyre, J.G. McIvor and K.M. Heard). CSIRO Publishing, Collingwood, Victoria.

McIvor, J.G., Williams, J. and Gardener, C.J. (1995) Pasture management influences runoff and soil movement in the semi-arid tropics. *Australian Journal of Experimental Agriculture* **35**, 55-65.

McIvor, J.G., McIntyre, S., Saeli, I. and Hodgkinson, J.J. (2005) Patch dynamics in grazed subtropical native pastures in south-east Queensland. *Austral Ecology* **30**, 445-464.

McKenzie, N., Jacquier, D., Isbell, R. and Brown, K. (2004) *Australian Soils and Landscapes*. CSIRO Publishing, Collingwood, Victoria.

Mills, A.J. and Fey, M.V. (2004) Frequent fires intensify soil crusting: physicochemical feedback in the pedoderm of long-term burn experiments in South Africa. *Geoderma* **121**, 45-64.

Moreira, M.Z., Scholz, F.G., Bucci, S.J., Sternberg, L.S., Goldstein, G., Meinzer, F.C. and Franco, A.C. (2003) Hydraulic lift in a neotropical savanna. *Functional Ecology* **17**, 573-581.

Morgan, J.W. (1998a) Importance of canopy gaps for recruitment of some forbs in *Themeda triandra*-dominated grasslands of south-eastern Australia. *Australian Journal of Botany* **46**, 609-627.

Morgan, J.W. (1996) Secondary juvenile period and community recovery following late-spring burning of a Kangaroo Grass *Themeda triandra* grassland. *Victorian Naturalist* **113**, 47-57.

Morgan, J.W. (2001) Seedling recruitment patterns over 4 years in an Australian perennial grassland community with different fire histories. *Journal of Ecology* **89**, 908-919.

Morgan, J.W. and Lunt, I.D. (1999) Effects of time-since-fire on the tussock dynamics of a dominant grass (*Themeda triandra*) in a temperate Australian grassland. *Biological Conservation* **88**, 379-386.

Morrison, D.A. (1995) Some effects of low-intensity fires on populations of co-occurring small trees in the Sydney region. *Proceedings of the Linnean Society of NSW* **115**, 109-119.

Morrison, D.A. and Renwick, J.A. (2000) Effects of variation in fire intensity on regeneration of co-occurring species of small trees in the Sydney region. *Australian Journal of Botany* **48**, 71-79.

Morrison, D.A., Buckney, R.T., Bewick, B.J. and Cary, G.J. (1996) Conservation conflicts over burning bush in south-eastern Australia. *Biological Conservation* **76**, 167-175.

Nadolny, C., Ranclaud, H., Whalley, W., McLeish, T., Wheeler, J., Morsley, R., Croft, P., McCormick, L., Ede, A., Hawes, W., Watson, C. and Austin, J. (2003) *Grassy Vegetation in North-Western NSW and Guidelines for its Management for Conservation*. Armidale Tree Group, Armidale, NSW.

Neumann, F.G. and Tolhurst, K. (1991) Effects of fuel reduction burning on epigeal arthropods and earthworms in dry sclerophyll eucalypt forest of west-central Victoria. *Australian Journal of Ecology* **16**, 315-330.

Noble, I.R. (1980) Interactions between tussock grass (*Poa* spp.) and *Eucalyptus pauciflora* seedings near treeline in south-eastern Australia. *Oecologia* **45**, 350-353.

Noble, I.R. (1984) Mortality of lignotuberous seedlings of *Eucalyptus* species after an intense fire in montane forest. *Australian Journal of Ecology* **9**, 47-50.

Noble, J.C. (1982) The significance of fire in the biology and evolutionary ecology of mallee *Eucalyptus* populations. Pp. 153-159 in *Evolution of the Flora and Fauna of Arid Australia* (ed. by W.R. Barker and P.J.M. Greenslade). Peacock Publications, Adelaide.

Noble, J.C. (1997) *The Delicate and Noxious Scrub: CSIRO Research into Native Tree and Shrub Proliferation in the Semi-arid Woodlands of Eastern Australia*. CSIRO Division of Wildlife and Ecology, Canberra.

Noble, J.C. (2004) *Effectiveness of Grazing on Fire Hazard Reduction and Impact on Conservation of Native and Other Grasslands in the Australian Capital Territory*. Report No. 11, ACT Bushfire Projects. ACT Department of Urban Services, Canberra. On line at http://www.urbanservices.act.gov.au/stateofknowledgesummaries.html. Accessed 23 June 2005.

Noble, J.C. and Grice, A.C. (2002) Fire regimes in semi-arid and tropical pastoral lands: managing biological diversity and ecosystem function. Pp. 373-400 in *Flammable Australia: the Fire Regimes and Biodiversity of a Continent* (ed. by R.A. Bradstock, J.E. Williams and A.M. Gill). Cambridge University Press, Cambridge.

Odgers, B.M. (1999) Seasonal variation in buried germinable seed banks of grass species in an urban eucalypt forest reserve. *Australian Journal of Botany* **47**, 623-638.

Ojima, D.S., Schimel, D.S., Parton, W.J. and Owensby, C.E. (1994) Long- and short-term effects of fire on nitrogen cycling in tallgrass prairie. *Biogeochemistry* **24**, 67-84.

Oliver, I., Pearce, S., Greenslade, P.J.M. and Britton, D.R. (2006) Contribution of paddock trees to the conservation of terrestrial invertebrate biodiversity within grazed native pastures. *Austral Ecology* **31**, 1-12.

Orr, D.H. and Paton, C.J. (1997) Using fire to manage species composition in *Heteropogon contortus* (black speargrass) pastures. 2. Enhancing the effects of fire with grazing management. *Australian Journal of Agricultural Research* **48**, 803-810.

Orr, D.M., McKeon, G.M. and Day, K.A. (1991) Burning and exclosure can rehabilitate degraded black spear grass (*Heteropogon contortus*) pastures. *Tropical Grasslands* **25**, 333-336.

Orr, D.M., Paton, C.J. and Lisle, A.T. (1997) Using fire to manage species composition in *Heteropogon contortus* (black speargrass) pastures. 1. Burning regimes. *Australian Journal of Agricultural Research* **48**, 795-802.

Paton, C.J. and Rickert, K.G. (1989) Burning, then resting, reduces wiregrass (*Aristida* spp.) in black speargrass pastures. *Tropical Grasslands* **23**, 211-218.

Pieper, R.D. (1990) Overstory-understory relations in pinyon-juniper woodlands in New Mexico. *Journal of Range Management* **43**, 413-415.

Prober, S.M. and Brown, A.H.D. (1994) Conservation of the grassy white box woodlands: population genetics and fragmentation of *Eucalyptus albens*. *Conservation Biology* **8**, 1003-1013.

Prober, S.M. and Thiele, K.R. (1995) Conservation of the grassy White Box woodlands: relative contributions of size and disturbance to floristic composition and diversity of remnants. *Australian Journal of Botany* **43**, 349-366.

Prober, S.M., Lunt, I.D. and Thiele, K.R. (2002a) Determining reference conditions for management and restoration of temperate grassy woodlands: relationships among trees, topsoils and understorey flora in little-grazed remnants. *Australian Journal of Botany* **50**, 687-697.

Prober, S.M., Thiele, K.R. and Lunt, I.D. (2002b) Identifying ecological barriers to restoration in temperate grassy woodlands: soil changes associated with different degradation states. *Australian Journal of Botany* **50**, 699-712.

Prober, S.M., Thiele, K.R. and Koen, T.B. (2004) Spring burns control exotic annual grasses in a temperate grassy woodland. *Ecological Management and Restoration* **5**, 131-134.

Prober, S.M., Thiele, K.R., Lunt, I.D. and Koen, T.B. (2005) Restoring ecological function in temperate grassy woodlands: manipulating soil nutrients, exotic annuals and native perennial grasses through carbon supplements and spring burns. *Journal of Applied Ecology* **42**, 1073-1085.

Prosser, I.P. and Williams, L. (1998) The effect of wildfire on runoff and erosion in native *Eucalyptus* forest. *Hydrological Processes* **12**, 251-265.

Proulx, M. and Mazumder, A. (1998) Reversal of grazing impact on plant species richness in nutrient-poor vs. nutrient-rich ecosystems. *Ecology* **79**, 2581-2592.

Raison, R.J., Woods, P.V. and Khanna, P.K. (1983) Dynamics of fine fuels in recurrently burnt eucalypt forests. *Australian Forestry* **46**, 294-302.

Raison, R.J., O'Connell, A.M., Khanna, P.K. and Keith, H. (1993) Effects of repeated fires on nitrogen and phosphorus budgets and cycling processes in forest ecosystems. Pp. 347-363 in *Fire in Mediterranean Ecosystems* (ed. by L. Trabaud and R. Prodon). Commission of the European Communities, Brussels-Luxembourg.

Read, T.R., Bellairs, S.M., Mulligan, D.R. and Lamb, D. (2000) Smoke and heat effects on soil seed bank germination for the re-establishment of a native forest community in New South Wales. *Austral Ecology* **25**, 48-57.

Redpath, P. (2005) *Partridge Creek Acid Sulfate Soil Hotspot Project Targeted Fauna Survey - Post Works Monitoring*. Department of Natural Resources, Grafton.

Reseigh, J., Nadolny, C. and Reid, N. (2003) *Effects of recent changes in grazing and fertiliser management on species richness of native ground-layer vegetation, Northern Tablelands, New South Wales*. Pp 1-5 in Proceedings of the Conference on Rural Land Use Change.

Richards, J.H. and Caldwell, M.M. (1987) Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. *Oecologia* **73**, 496-489.

Robertson, D. (1985) *Interrelationships between Kangaroos, Fire and Vegetation Dynamics at Gellibrand Hill Park, Victoria*. PhD thesis, University of Melbourne.

Roche, S., Dixon, K.W. and Pate, J.S. (1998) For everything a season: smoke-induced seed germination and seedling recruitment in a Western Australian *Banksia* woodland. *Australian Journal of Ecology* **23**, 111-120.

Scanlan, J.C. and Burrows, W.H. (1990) Woody overstorey impact on herbaceous understorey in *Eucalyptus* spp. communities in central Queensland. *Australian Journal of Ecology* **15**, 191-197.

Scholes, R.J. and Archer, S.R. (1997) Tree-grass interactions in savannas. *Annual Review of Ecology and Systematics* **28**, 517-544.

Semple, W.S. and Koen, T.B. (2003) Effect of pasture type on regeneration of eucalypts in the woodland zone of south-eastern Australia. *Cunninghamia* **8**, 76-84.

Shaw, N.H. (1957) Bunch spear grass dominance in burnt pastures in south-eastern Queensland. *Australian Journal of Agricultural Research* **4**, 325-334.

Shea, S.R., McCormick, J. and Portlock, C.C. (1979) The effect of fires on regeneration of leguminous species in the northern Jarrah (*Eucalyptus marginata* Sm) forest of Western Australia. *Australian Journal of Ecology* **4**, 195-205.

Simmons, D. and Adams, R. (1986) Fuel dynamics in an urban fringe dry sclerophyll forest in Victoria. *Australian Forestry* **49**, 149-154.

Simmons, D. and Adams, R. (1999) *Fuel loads and characteristics in some structurally diverse vegetation types in Victoria*. Paper presented at the Australian Bushfire Conference, Albury, July 1999. On line at http://life.csu.edu.au/bushfire99/papers/simmons/index.html. Accessed 6 June 2005.

Simpson, P. (2000) Balancing pasture development options for landscape diversity. Pp. 124-132 in *Balancing Conservation and Production in Grassy Landscapes* (ed. by T. Barlow and R. Thorburn). Proceedings of conference held in Clare, South Australia on 19-21 August 1999. Environment Australia, Canberra. On line at http://www.deh.gov.au/land/publications/grasscon/. Accessed 8 July 2005.

Sivertsen, D. (1993) Conservation of remnant vegetation in the Box and Ironbark lands of New South Wales. *Victorian Naturalist* **110**, 24-29.

Southwell, C.J. and Jarman, P.J. (1987) Macropod studies at Wallaby Creek III. The effect of fire on pasture utilisation by macropodids and cattle. *Australian Wildlife Research* **14**, 117-124.

Spooner, P., Lunt, I. and Robinson, W. (2002) Is fencing enough? The short-term effects of stock exclusion in remnant grassy woodlands in southern NSW. *Ecological Management and Restoration* **3**, 117-126.

Starr, T. (nd) *Fire Management at Ban Ban Springs, NT*. Case study produced by the Tropic Savannas CRC, Darwin. On line at http://savanna.ntu.edu.au/downloads/banban.pdf. Accessed 20 July 2005.

State Forests of New South Wales (2002) *Submission to the Joint Select Committee on Bushfires*.

Stone, C. (2005) Bell-miner-associated dieback at the tree crown scale: a multi-tropic process. *Australian Forestry* **68**, 237-241.

Stubbs, B.J. (2001) The 'grasses' of the Big Scrub district, north-eastern New South Wales: their recent history, spatial distribution and origins. *Australian Geographer* **32**, 295-319.

Tasker, E. (2002) *The Ecological Impacts of Cattle Grazing and Associated Grazier Burning in the Eucalypt Forests of Northern NSW*. PhD thesis, University of Sydney.

Tasker, E.M. and Bradstock, R.A. (submitted) The influence of cattle grazing practices on forest understorey structure in North-eastern New South Wales.

Tasker, E.M. and Dickman, C.R. (2004) Small mammal community composition in relation to cattle grazing and associated burning in eucalypt forests of the Northern Tablelands of New South Wales. Pp. 721-740 in *The Conservation of Australia's Forest Fauna (2nd edition)* (ed. by D. Lunney). Royal Zoological Society of New South Wales, Mosman, NSW.

Thomas, P.B., Morris, E.C. and Auld, T.D. (2003) Interactive effects of heat shock and smoke on germination of nine species forming soil seed banks within the Sydney region. *Austral Ecology* **28**, 674-683.

Tolhurst, K. (1996a) Effects of fuel reduction burning on fuel loads in a dry sclerophyll forest. Pp. 17-20 in *Fire and Biodiversity: the Effects and Effectiveness of Fire Management* (ed. by J.R. Merrick). Proceedings of conference held in Melbourne on 8-9 October 1994. Commonwealth Department of Environment, Sport and Territories, Canberra.

Tolhurst, K. (1996b) Effects of fuel reduction burning on flora in a dry sclerophyll forest. Pp. 97-107 in *Fire and Biodiversity: the Effects and Effectiveness of Fire Management* (ed. by J.R. Merrick). Proceedings of conference held in Melbourne on 8-9 October 1994. Commonwealth Department of the Environment, Sport and Territories, Canberra.

Tongway, D.J. and Ludwig, J.A. (1990) Vegetation and soil patterning in semi-arid mulga lands of eastern Australia. *Australian Journal of Ecology* **15**, 23-34.

Tothill, J.C. (1969) Soil temperatures and seed burial in relation to the performance of *Heteropogon contortus* and *Themeda australis* in burnt native woodland pastures in eastern Queensland. *Australian Journal of Botany* **17**, 269-275.

Tothill, J.C. (1971) Grazing, burning and fertilizing effects on the regrowth of some woody species in cleared open forest in south-east Queensland. *Tropical Grasslands* **5**, 31-34.

Tothill, J.C. (1992) Fire in Black Speargrass (*Heteropogon contortus*) pastures - a ten year comparison of burnt and unburnt treatments. Pp. 274-279 in *Fire Research in Rural Queensland: Selected Papers from the Queensland Fire Research Workshop Series 1980-1989* (ed. by B.R. Roberts). Land Use Study Centre, University of Southern Queensland, Toowoomba.

Trapnell, C.G. (1959) Ecological results of woodland burning experiments in northern Rhodesia. *Journal of Ecology* **47**, 129-168.

Tremont, R.M. (1994) Life-history attributes of plants in grazed and ungrazed grasslands on the Northern Tablelands of New South Wales. *Australian Journal of Botany* **42**, 511-530.

Trollope, S.W. and Trollope, L.A. (2004) *Prescribed burning in African grasslands and savannas for wildlife management*. Aridlands Newsletter No 55. Available at http://ag.arizona.edu/OALS/ALN/aln55/trollope.html. Accessed 9 March 2006.

Turner, J. and Lambert, M. (2005) Soil and nutrient processes related to eucalypt forest dieback. *Australian Forestry* **68**, 251-256.

Uys, R.G., Bond, W.J. and Everson, T.M. (2004) The effect of different fire regimes on plant diversity in southern African grasslands. *Biological Conservation* **118**, 489-499.

Vesk, P.A. and Westoby, M. (2001) Predicting plant species' responses to grazing. *Journal of Applied Ecology* **38**, 897-909.

Vlahos, S. and Bell, D.T. (1986) Soil seed-bank components of the northern jarrah forest of Western Australia. *Australian Journal of Ecology* **11**, 171-179.

Wahren, C.A., Papst, W.A. and Williams, R.J. (1994) Long-term vegetation change in relation to cattle grazing in subalpine grassland and heathland on the Bogong High Plains: an analysis of vegetation records from 1945-1994. *Australian Journal of Botany* **42**, 607-639.

Walker, J. (1981) Fuel dynamics in Australian vegetation. Pp. 101-127 in *Fire and the Australian Biota* (ed. by A.M. Gill, R.H. Groves and I.R. Noble). Australian Academy of Science, Canberra.

Walker, J. and Tothill, J.C. (1992) Fire in the grasslands of Queensland. Pp. 251-262 in *Fire Research in Rural Queensland: Selected Papers from the Queensland Fire Research Workshop Series 1980-1989* (ed. by B.R. Roberts). Land Use Study Centre, University of Southern Queensland, Toowoomba.

Walker, J., Moore, R.M. and Robertson, J.A. (1972) Herbage response to tree and shrub thinning in *Eucalyptus populnea* shrub woodlands. *Australian Journal of Agricultural Research* **23**, 405-410.

Walker, J., Raison, R.J. and Khanna, P.K. (1986a) Fire. Pp. 185-216 in *Australian Soils: the Human Impact* (ed. by R.S. Russell and R.F. Isbell). University of Queensland Press, St Lucia.

Walker, J., Robertson, J.A., Penridge, L.K. and Sharpe, P.J.H. (1986b) Herbage response to tree thinning in a *Eucalyptus crebra* woodland. *Australian Journal of Ecology* **11**, 135-140.

Walker, J., Malafant, K. and Edwards, J. (1992) The effects of fire on a *Themeda-Heteropogon* grassland near Rockhampton. Pp. 280-287 in *Fire Research in Rural Queensland: Selected Papers from the Queensland Fire Research Workshop Series 1980-1989* (ed. by B.R. Roberts). Land Use Study Centre, University of Southern Queensland, Toowoomba.

Watson, P.J. (2005) *Fire Frequencies for Western Sydney's Woodlands: Indications from Vegetation Dynamics*. PhD thesis, University of Western Sydney.

Watson, P. (2006) *Fire Frequency Guidelines and the Vegetation of the Northern Rivers Region. Draft 2*. Hotspots project, Nature Conservation Council of NSW, Sydney.

Watson, P. and Wardell-Johnson, G. (2004) Fire frequency and time-since-fire effects on the open-forest and woodland flora of Girraween National Park, south-east Queensland, Australia. *Austral Ecology* **29**, 225-236.

Wellington, A.B. and Noble, I.R. (1985) Post-fire recruitment and mortality in a population of the mallee *Eucalyptus incrassata* in semi-arid, south-eastern Australia. *Journal of Ecology* **73**, 645-656.

Weltzin, J.F. and Coughenour, M.B. (1990) Savanna tree influence on understory vegetation and soil nutrients in northwestern Kenya. *Journal of Vegetation Science* **1**, 325-334.

Whalley, R.D.B. (2000) Grasslands, grazing animals and people - how do they all fit together? *Tropical Grasslands* **34**, 192-198.

Whelan, R.J. (1995) *The Ecology of Fire*. Cambridge University Press, Cambridge.

Whelan, R.J. and Baker, J.R. (1999) Fire in Australia: coping with variation in ecological effects of fire. Pp. 71-79 in *Bush Fire Management Conference Proceedings: Protecting the Environment, Land, Life and Property* (ed. by F. Sutton, J. Keats, J. Dowling and C. Doig). Proceedings of conference held in Sydney on 27-28 February 1998. Nature Conservation Council of NSW, Sydney.

Williams, P.R., Congdon, R.A., Grice, A.C. and Clarke, P.J. (2004) Soil temperature and depth of legume germination during early and late dry season fires in a tropical eucalypt savanna of north-eastern Australia. *Austral Ecology* **29**, 258-263.

Williams, P.R., Congdon, R.A., Grice, A.C. and Clarke, P.J. (2005) Effect of season of burning and removal of herbaceous cover on seedling emergence in a eucalypt savanna of north-eastern Australia. *Austral Ecology* **30**, 491-496.

Williams, P.R., Congdon, R.A., Grice, A.C. and Clarke, P.J. (in preparation) Poor seedling survival limits plant recruitment in a tropical savanna of north-eastern Australia.

Williams, R.J., Cook, G.D., Ludwig, J.A. and Tongway, D. (1997) *Torch, trees, teeth and tussocks: disturbance in the tropical savannas of the Northern Territory*. Available on line at http://life.csu.edu.au/esa/esa97/papers/williams/williams.htm,

Williams, R.J., Cook, G.D., Gill, A.M. and Moore, P.H.R. (1999) Fire regime, fire intensity and tree survival in a tropical savanna in northern Australia. *Australian Journal of Ecology* **24**, 50-59.

Williams, R.J., Griffiths, A.D. and Allan, G.E. (2002) Fire regimes and biodiversity in the savannas of northern Australia. Pp. 281-304 in *Flammable Australia: the Fire Regimes and Biodiversity of a Continent* (ed. by R.A. Bradstock, J.E. Williams and A.M. Gill). Cambridge University Press, Cambridge.

Wimbush, D.J. and Costin, A.B. (1979) Trends in vegetation at Kosciusko. I. Grazing trials in the subalpine zone, 1957-1971. *Australian Journal of Botany* **27**, 741-487.

Winter, W.H. (1987) Using fire and supplements to improve cattle production from monsoon tallgrass pastures. *Tropical Grasslands* **21**, 71-81.

Withers, J. and Ashton, D.H. (1977) Studies on the status of unburnt *Eucalyptus* woodland at Ocean Grove, Victoria. I. The structure and regeneration. *Australian Journal of Botany* **25**, 623-637.

Wood, P.D. (2001) *What are the Germination Signals of the Cumberland Plain Woodland Soil Seed Bank?* Honours thesis, University of Western Sydney.

Woods, P.V., Raison, R.J. and Khanna, P.K. (1983) Effects of prescribed burning on forest-floor microclimate and on subsequent rates of litter decomposition in a *Eucalyptus pauciflora* forest. *Proceedings of the Ecological Society of Australia* **12**, 174-175.

York, A. (1997) *Impacts of Grazing and Burning on Forest Biodviersity. Initial Report to the Resource and Conservation Assessment Council.* The Key Centre for Biodiversity and Bioresources, Macquarie University, Sydney.

York, A. (1998) *Impacts of Grazing and Burning on Forest Biodviersity. Second Report to the Resource and Conservation Assessment Council.* The Key Centre for Biodiversity and Bioresources, Macquarie University, Sydney.

York, A. (1999a) Long-term effects of repeated prescribed burning on forest invertebrates: management implications for the conservation of biodiversity. Pp. 181-266 in *Australia's Biodiversity - Responses to Fire. Plants, Birds and Invertebrates* (ed. by A.M. Gill, J.C.Z. Woinarski and A. York). Department of the Environment and Heritage, Canberra.

York, A. (1999b) *Impacts of Grazing and Burning on Forest Biodiversity. Third and Final Report to the Resource and Conservation Assessment Council.* The Key Centre for Biodiversity and Bioresources, Macquarie University, Sydney.

York, A. and Tarnawski, J. (2004) Impacts of grazing and burning on terrestrial invertebrate assemblages in dry eucalypt forests of north-eastern New South Wales: implications for biodiversity conservation. Pp. 845-859 in *The Conservation of Australia's Forest Fauna (2nd edition)* (ed. by D. Lunney). Royal Zoological Society of New South Wales, Mosman, NSW.