Getting to the root of the issue: Review of eucalypt decline and dieback in relation to lack of low intensity fire management across Australia

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Contents

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1 Introduction

Exclusion of frequent low intensity mild fire as a primary cause of eucalypt decline in Australian native forests and woodlands has been inadequately recognised in many studies, research, papers, articles, reviews, management plans, legislation, policies and reports on land and fire management.

However, there are a considerable number of research papers and authors who have identified exclusion of low intensity fire as a/ the major cause of eucalypt decline across a number of Australian native forests and woodlands, as outlined in this review.

This review focusses solely on the issue of exclusion of frequent low intensity fire as a/ the primary cause of eucalypt decline in Australian native forests and woodlands.

The review is designed to:

- examine the issue in detail.
- provide integration of key information in one place to better assist readers.
- tease out the key issues in relation to low intensity fire and eucalypt decline in a manner with important research text available to assist readers in understanding the key information, issues and key references in relation to the matter.
- Identify key research authors in relation to establishing root cause of eucalypt decline relating to soil changes associated with inadequate low intensity fire.
- Identify key issues including extent of the issue across Australia, consequences, opportunities and case studies as well as the importance of adaptive management.

There are extensive examples of forest decline across the world and these issues aren't examined in this review, except briefly for adaptive land management in the US and a small number of references.

Key details in regards to eucalypt decline and dieback in Australia are outlined in Section 2 of the review. The extent of eucalypt decline across Australia is extensive and increasing.

Lack of low intensity fire and eucalypt decline across Australia is explored in considerable depth in Section 3. Exclusion of low-intensity fire is increasingly the common land management practice in south-eastern Australia and this is the major contributor to eucalypt decline in Australia.

Lack of low intensity fire, eucalypt decline and the link to soil factors is explored in great depth in Section 4. Key soil factors relate to pH, nitrogen, phosphorus availability, N:P ratio, C:N ratio, organic matter, soil wetness, mycorrhizae and other soil microbiota in some cases.

Other factors in relation to lack of low intensity fire and eucalypt decline is explored in depth in Section 5.

Model processes of changed land management, eucalypt decline and dieback is outlined in depth in Section 6.

Other references in regards to low intensity fire and grazing and eucalypt decline in Australia that can be read are outlined in Section 7.

A number of Australian eucalypt decline case studies in relation to lack of low intensity fire and grazing are highlighted in Section 8.

As explained in Section 9, there are extensive negative consequences of lack of low intensity fire and resultant eucalypt decline and these consequences have been identified.

As outlined in Section 10, there are extensive US actions underway to improve forest health, reduce forest decline, and resilience and reduce bushfire risk in the US, in many cases this provides a model for Australia to start seriously addressing eucalypt decline.

As outlined in Section 11, the importance of adaptive management in relation to low intensity fire and grazing in Australian forests to soundly address eucalypt decline is outlined. Low intensity fire in SE Australian states is of the order of 1 %.of forest area per year, an extremely low rate, contributing to the increase in eucalypt decline.

As outlined in Section 12, there opportunities for targeted fire and land management studies and research in relation to eucalypt decline and regular low intensity fire. There are opportunities in both areas.

2 Key issues in regards to eucalypt decline and dieback in Australia

Key issues in regards to eucalypt decline and dieback in Australia are considered in detail in sections 2.1 to 2.3 below.

2.1 The difference between eucalypt decline and dieback

Jurskis (2008) sums up the difference between eucalypt decline and dieback well:

Drought has been proposed as a primary cause of tree diebacks and declines around the world, and was considered to be the major cause of many rural and forest tree declines in Australia. However, drought may be used as a 'scapegoat' when the underlying causes of tree decline are controversial or cannot be readily identified. Confusion arises from a failure to distinguish between dieback and chronic decline of trees. Diebacks are associated with natural climatic extremes such as drought, and recovery occurs once conditions ameliorate. Chronic declines are associated with environmental changes caused by human management, and trees continue to decline after climatic conditions improve. Diebacks and declines usually produce different patterns of stressed trees in the landscape and have different impacts on forest understoreys. Silvicultural thinning can reduce the impacts of drought but may exacerbate chronic decline. Drought can have a role in accelerating chronic decline, but only where there have been other environmental changes. It is not a primary cause of tree decline.

Jurskis (2005 a) further explains this:

Ongoing monitoring of eucalypt decline during recent droughts in eastern Australia, together with extensive one-time observations across temperate Australia, provided opportunities to further examine some hypotheses of decline and dieback that were largely based on retrospective investigations.

Episodes of dieback can be distinguished from the process of chronic decline. Dieback episodes were associated with natural climatic extremes whereas chronic decline was associated with human management. Decline of forests in nature reserves was associated with exclusion of fire and grazing, while decline of rural trees was mostly associated with pasture improvement. Trees growing low in the landscape on soils with poor drainage and aeration were especially predisposed to decline. It appears that chronic abiotic stress causes tree decline when the function of roots is impaired by changes in soils. Climatic extremes can accelerate chronic declines associated with human management. A variety of pests, 'pathogens' and parasites can take advantage of trees that are stressed by environmental changes, especially eutrophication. Similarities between diebacks and declines in the Atlantic and Pacific regions suggest a simple unifying concept of tree decline and dieback.

Jurskis (2008) sums this difference up:

Diebacks and declines usually produce different patterns of stressed trees in the landscape and have different impacts on forest understoreys.

Jurskis (2016) observes in relation to chronic decline:

… chronic decline involving a wide range of arbivores has affected a wide range of eucalypts across Australia since European settlement, and is currently rampant in many areas of forest and woodland. Pasture improvement and/or exclusion of fire and grazing are the major causes of chronically declining health of eucalypts.

Further detail in relation to chronic decline is highlighted in Sections 2.3, 3.2, 3.3 and 5.2. It is noted that chronic decline has been accelerated/ extended by waterlogging in the floods that inevitably end droughts. Especially after the millennium drought, when blackbutt and spotted gum on well drained soils in NSW started to decline.

2.2 Key characteristics of decline and dieback and the pattern of eucalypt decline in the landscape

The Bushfire CRC (2007) consider this issue:

While variations occur in the characteristics of dieback across forests and locations, there is a significant degree of commonality. In individual tree crowns dieback commences with loss of foliage, followed by dieback of small branches in conjunction with re-sprouting from epicormic buds. With time, epicormic derived foliage comes to dominate, the tree crown becomes very thin and many dead branches are evident. Crown and tree death complete the process. Tree decline varies over time, with increases in intensity in some years followed by a period of regrowth, *but overall there is a pattern of gradual deterioration. The intensity of dieback sometimes increases with the occurrence of drought although drought is rarely considered to be the primary cause of decline.*

Turner et al. (2008) notes the association between declining tree health in the long unburnt areas is related to changes in soil characteristics:

In the subsidiary study of paired plots found there was declining tree health in the long unburnt areas related to changes in soil characteristics, compared with the adjacent regularly burnt areas.

Jurskis (2004 a) lists common denominators of decline:

- *Site factors predispose stands to decline*
- *Fungi and insects are contributing factors that are "given too much credit"*
- *Feeder roots and mycorrhizae degenerate before the onset of above-ground symptoms*
- *Dry forests are changing structurally and florlistically*
- *Pests and pathogens are spreading across the landscape, reinforcing the vegetation changes*
- *Ecological processes including fire, pest and disease outbreaks are happening at unnatural temporal and spatial changes.*

Jurskis (2011 a) elucidates the pattern of eucalypt decline in the landscape*:*

Declining stands are usually associated with relatively flat or concave sites low in the landscape with soils that are not well drained or aerated and are poorly buffered against acidification and related changes. This is where changes in soil chemistry (N, pH and Al) are most pronounced and where tree roots are physically challenged. Poorly structured soils are associated with particular geological substrates and there are particular eucalypt species or combinations of species that are associated with such soils and sites in any given region. Thus information about geology, landform and forest type can be used to identify eucalypt forests in each region that are predisposed to decline if managed inappropriately.

Jurskis (2004 a) provides useful information in relation to eucalypt decline:
In coastal NSW, decline ……It is particularly associated with concave topography, depositional soils, naturally grassy forest types, private land and "under-reserved" forest types. These naturally open grassy forests evolved with frequent low intensity fire from lightning and aboriginal burning.

and:

Aside from long term experiments you can see evidence in the landscape of the impacts of changed fire regimes. Contrasts in forest health due to different fire regimes are often visible:

- *Between the top and bottom sides of roads*
- *On opposite sides of tenure boundaries*
- *Between drainage lines and spurs*
- *Between reserves and general management zones*

It is important to note that there is rapid expansion of eucalypt decline across Australia as noted by Jurskis (2015), this is outlined in Section 2.3, and characteristics of eucalypt decline have changed.

The case study section, Section 8, outlines the pattern of eucalypt decline further.

2.3 Extent of eucalypt decline across Australia

Jurskis (2015) provides detail in relation to the extent of eucalypt decline:

From Firestick Ecology (in 2015): Chronic decline is extending through eucalypt ecosystems across Australia. It affects almost 20% of forests and woodlands in coastal New South Wales, whilst more than 50% of eucalypt systems in Queensland's wet tropics are declining. Decline is widespread in Victoria, Tasmania and the south-west of Western Australia, but reliable figures are not available. Forest pathologists are mostly ignorant of the fundamental problem and the simple solution. Australia's State of the Forests report for 2013 reflected their confusion:

Many pests and diseases, particularly native ones, exhibit cyclical patterns of impact on native forests, and are generally of minor overall concern. … A wide range of persistent or intermittent crown dieback syndromes occurs to some degree in native forests in all states and territories, often resulting in significant tree mortality and associated ecosystem impacts. These syndromes are usually caused by combinations of factors such as climatic stresses, poor land management practices, severe insect attacks, and an imbalance in insect predator levels; ameliorating their impacts through forest management can be difficult.

Jurskis and Turner (2002) note that the reduced application of low- intensity fire is a common agent of changed soil conditions:

A simple model of eucalypt dieback is proposed to account for both rural and forest dieback, including an increasing range of 'susceptible' species and sites. It associates eucalypt dieback with increased soil moisture and nitrogen status that stresses the roots of established eucalypt trees. These changes affect the physiology of the trees and encourage high rates of folivory and/or fungal pathogenicity. This model can encompass dieback from dryland salinity, 'high-altitude' dieback in Tasmania, 'bellbird' dieback, 'koala' dieback in Victoria and South Australia, phasmatid outbreaks in New South Wales and Victoria, and potentially extends to 'regrowth' dieback in Tasmania.

Jurskis (2005 b) details the extent of eucalypt decline across Australian states, including Table 1 of the paper.

There is rapid expansion of eucalypt decline across Australia as noted by Jurskis (2015) in Chapter 12:

Chronic eucalypt decline has expanded greatly across Australia in the new millennium. Increasing restrictions on mild burning have made forests increasingly vulnerable to drought and waterlogging. With the Millennium and Black Summer Droughts, followed by the inevitable flooding rains that brought them to an end, forests on relatively fertile and well drained sites have rapidly succumbed. The flush of soft young growth across broad areas consequent to the Black Summer fires has led to plagues of foliovores, fungi etc. contributing the problem. Our naturally most resilient forest types such as high quality blackbutt and spotted gum on relatively fertile, well drained sites have rapidly deteriorated. Scrub understories have proliferated compounding the problem. It has become obvious that all sclerophyll forest types, dry and moist, have lost resilience in the absence of mild fire regimes. The distinction between high and dry areas prone to drought scorch and low-lying poorly drained areas prone to chronic decline has disappeared. During the Millennium Drought, drought scorch overlapped with chronic decline. The myths of wet sclerophyll forests, actually scrubbed-up moist eucalypt forests, and natural succession to rainforest have been exposed. Sclerophyll overstoreys declined whilst mesic understoreys continued to boom. High quality karri forests with dense subcanopies of both mesic and sclerophyll vegetation have increasingly suffered chronic decline. The only eucalypt forest types that remain unaffected by chronic decline in the absence of sustainable management are small and isolated patches of mixed eucalypt forest over genuine rainforest subcanopies. These grow on fertile well-structured soils which are occasionally affected by severe droughts. These unusual stands could be described as wet sclerophyll but are probably better described as mixed forests.

3 Lack of low intensity fire and eucalypt decline across Australia

Lack of fire and eucalypt decline across Australia is considered in detail in sections 3.1 to 3.7 below.

3.1 Historical identification of Eucalypt decline in Australia and changed fire regimes

Jurskis (2011 a) notes the observations of the famed explorer Howitt outlined in 1890:

I have said that in my opinion the increased growth of the Eucalyptus forests since the first settlement of Gippsland has been largely due to the checking of the bush fires year by year, and to the increase thereby of the chance survival of the seedling Eucalypts, and to the same cause we may assign the increase of the leaf-eating insects which seem in places to threaten the very existence of the Red Gum. Bush fires, which swept the country more or less annually, kept down the enormous multiplication of insect life, destroying myriad's of the grass hoppers and caterpillars, which now devastate parts of the Gippsland district, spoiling the oat crops, and eating the grass down to the ground.

The ravages of the larvae of Lepidoptera are at present greatly aided by the sickly state in which many of the Red Gum forests in Gippsland now are.

Howitt observed correctly in regards to the increased growth of eucalypts, and ill health of some species but not the cause of the insect increase, a likely secondary contributor. An important reference for Howitt is outlined below Howitt AW (1890) The eucalypts of Gippsland. Transactions of the Royal Society of Victoria **II**, 81–120.

Another important reference information source in relation to this matter is Jurskis (2011 b).

White (1986) makes observations in regards to New England and Victorian decline in the late 1800's:

On the New England Tablelands in Australia between 1950 and 1980 very many eucalypts declined and died……………..Several species of Eucalyptus were affected, but those species which normally grow on poorly drained sites died first and continued, even on better sites, to be the species worst and most frequently affected. Declining trees were heavily and repeatedly attacked by defoliating insects. The same species had declined and died in the same localities approximately 100 years earlier.

and:
MacPherson (1886) reported that from 1862 to 1874 there had been extensive death of trees in the country between Geelong and Ballarat in Victoria.

White (1986) also makes observations in regards to Western Australia in the late 1920’s:

The dieback and death of Jarrah trees (Eucalyptus marginata) in the dry schlerophyll forests of Western Australia has been extensively studied and reported (Podger 1973). It was first noticed in the 1920s as a few patches of dead and dying trees which gradually in- creased in size and number, coalescing into extensive areas of dieback. Note that Podger (1973) reference is included in the other reference list in Section 7.

3.2 Detail in relation to the cause of eucalypt decline across Australia in relation to lack of fire

Jurskis (2015) summarises detail in relation to the cause of eucalypt decline:

One hundred and fifty years ago, Howitt recognised chronic decline of red gum defoliated by insects in East Gippsland as a consequence of not burning. Twenty-five years ago Bob Ellis working in forests, and Jill Landsberg working in woodland pastures, elucidated connections between soil changes, tree physiology and chronic decline. Not burning native pastures, or sowing and fertilising exotic pastures, have similar effects on soils, tree roots, resilience to drought and waterlogging, and food quality of trees for arbivores. From the mid-twentieth century, a government bounty on fertilisers was responsible for an upsurge in rural tree decline. Since the late-twentieth century, expansion of conservation reserves, and reduction of burning in native forests and woodlands has caused a resurgence of forest decline.

Jurskis (2016) notes:
Pasture improvement and/or exclusion of fire and grazing are the major causes of chronically declining health of eucalypts.

Jurskis (2004 b) in his Gottstein Fellowship Report highlights:

A wider range of observations now suggests that dieback is associated with a variety of dry and moist forests that have been affected by reductions in the extent of prescribed burning in recent decades. A variety of pests, pathogens and parasites are contributing to the declines. All ages are affected except for young regrowth stands less than about 30 years old.

Jurskis (2004 c) outlines what happens with exclusion of fire:

- makes soils cool moist and N-rich
- makes eucalypt leaves young, moist and N-rich
- promotes mycorrhizal dysfunction
- promotes root ‘pathogens’
- promotes ‘arbivory’

Jurskis (2011 a) explains:

The patterns and processes described here are in agreement with studies conducted in Tasmania, Western Australia and elsewhere around the globe on the causes of tree decline. These studies show the importance of prescribed burning to the nutrition and health of forests and that nutrient cycles should be an important consideration in planning a healthy fire regime. in Western Australia prescribed burning has been more widely and consistently used with greater public support than in eastern Australia.

Jurskis and Turner (2002) note that the reduced application of low- intensity fire is a common agent of changed soil conditions:

A simple model of eucalypt dieback is proposed to account for both rural and forest dieback, including an increasing range of ‘susceptible’ species and sites. It associates eucalypt dieback with increased soil moisture and nitrogen status that stresses the roots of established eucalypt trees. These changes affect the physiology of the trees and encourage high rates of folivory and/or fungal pathogenicity. This model can encompass dieback from dryland salinity, ‘high-altitude’ dieback in Tasmania, ‘bellbird’ dieback, ‘koala’ dieback in Victoria and South Australia, phasmatid outbreaks in New South Wales and Victoria, and potentially extends to ‘regrowth’ dieback in Tasmania. Reduced application of low- intensity fire is a common agent of changed soil conditions.

St Clair and Jurskis (2010) further note:

Large areas of forest in temperate Australia are suffering chronic decline in health. Much of the affected area is expected to become more arid, exacerbating forest decline and fire risks.

Exclusion of frequent low intensity fire from fire dependent forests and woodlands results in changes in the physical and chemical properties of soils including acidification and nutrient imbalances. Eucalypt roots are affected leading to chronic decline and altered ecological interactions with competitors, pests, parasites and diseases. Fuels build up in *weight and vertical profile, and seasonal flammability is altered increasing fire risks and leading to the 'megafire' phenomenon.*

Turner and Lambert (2005) provide additional detail in relation to crown dieback (refer to decline detail below this): *Crown dieback is occurring in extensive areas of eucalypt forest in east coast Australia. While there is variation across sites and species with regard to the rate and intensity of the development of dieback, there are indications of common causative factors. ……..Evidence indicates that nutrients are a primary factor. Nutrient depletion from soils through the process of immobilisation in biomass as a stand grows has been suggested as a cause, but there is no evidence for this hypothesis. There is evidence of long-term accumulation of nitrogen (total and available) in undisturbed stands, and this leads to nutrient and biochemical imbalances in the foliage together with root morphological changes. Biochemical changes include increases and imbalances in amino acids resulting in the foliage being more attractive to folivores, and consequent increased herbivory. The level of insects or other folivores is a symptom of the problem and not a primary cause of dieback. Regular burning maintains reasonably stable levels of nitrogen within the system and these levels are the long-term norm for many eucalypt ecosystems. Essentially, lack of regular low-intensity burning can lead to reduced stand health and growth, and, in the longer term, changes in stand structure.*

It is important to note that Jurskis and Turner (2002) define dieback that includes decline of large areas of trees: "*Dieback in this discussion refers to the deterioration and death of stands of trees or large areas of trees rather than individual trees. This is sometimes termed tree decline ….".* In addition, Jurskis (2008) clearly sums up the difference between eucalypt decline and dieback.

There is a range of other good evidence to support the close association of inadequate low intensity fire and eucalypt decline and dieback:

- Attiwill (1994).
- Bowling and McLeod (1968).
- Gleadow and Ashton (1981).
- Jurskis (2000).
- Lunt (1998).
- Rose S (1997).
- Many other references in this document.

3.3 Processes that cause forest decline when fire is excluded from fire dependent ecosystems

Jurskis and Walmsley (2012) note:

Most eucalypt ecosystems depend on frequent low intensity fire to maintain natural nutrient cycles and the balance between established trees and their competitors and arbivores. Absence of frequent fire alters these processes and sometimes allows mass establishment of fire sensitive seedlings. Mature trees can be affected directly by the soil changes and indirectly by enhanced competition and arbivory. This can result in chronic decline of eucalypts and gross changes in the structure and composition of ecosystems. Some species and provenances appear to be genetically predisposed to enhanced arbivory whilst some sites are physically and chemically predisposed to deleterious changes in soil conditions. Thus information on species/site combinations can be used to identify ecosystems that are predisposed to chronic decline in the absence of fire.

Jurskis (2016) further explains (note references removed here):

- Declining trees are usually evident in ungrazed and unburnt areas . . .
- Retained trees in unimproved grazing paddocks or paddocks where crops have been harvested are often healthy compared to similar trees in improved pastures
- Grazing, cropping and/or burning can maintain healthy soil conditions for eucalypts, as did Aboriginal burning over about 40 millennia in dry and moist eucalypt forests across Australia.

Based on rates of N accumulation in the absence of fire and N removal by prescribed burning, Turner et al. (2008) suggests a return fire period of 5 years*:*

To maintain a stable C/N ratio with low mineral N production, a fire periodicity is required where N losses are about equivalent to N inputs. If inputs of N were about 12 kg N ha1 year1 and losses in low intensity fire were 65 kg N ha1, a period between fires of about 5 years would maintain stability. This would vary according to the fertility of the soil and the fire intensity.

3.4 Predisposition to eucalypt decline in forests without disturbance such as fire

Jurskis (2011 a) provides useful information in relation to declining stands at the time:

Declining stands are found in areas of poorly drained or aerated soils, with pronounced changes in soil chemistry and microclimate and challenged tree roots. Particular eucalypt species are associated with particular affected soils, meaning information about geology, landform and type of forest can be used to identify eucalypt forests with a predisposition to decline if managed inappropriately.

An estimated 790,000 hectares of New south Wales forests – 18 per cent of eucalypt forests in the study area – were predisposed to decline without such active management as burning, grazing or slashing.

Jurskis and Walmsley (2012) provide a good basis to explain forests predisposed to decline in 2012:

In New South Wales relatively unmodified eucalypt ecosystems mainly occur near the coast. We gathered observations of declining eucalypt ecosystems along the coast and used coarse GIS layers to estimate the extent and distribution of species and site combinations that are predisposed to decline. We estimated that 790,000 hectares, about 18% of the total area, of forests and woodlands in our study area may be predisposed to decline if managed inappropriately. About half the area is private land and half is in conservation reserves and multiple use forests. This preliminary estimate may help to focus attention on areas where adaptive management is necessary to conserve or restore healthy, diverse ecosystems and areas where further investigations are required to identify forests that are predisposed to decline.

Jurskis and Walmsley (2012) also identify factors in relation to decline predisposition:

- *Some eucalypts appear to be predisposed to decline throughout their range suggesting a genetic predisposition and/or a fidelity to difficult sites. Along the New South Wales coast these include Angophora floribunda, E. acmenoides, E. angophoroides, E. bosistoana, E. botryoides, E. consideniana, E. elata, E. longifolia, E. ovata, E. radiata, E. robusta, E. tereticornis and its close relatives …………….These species typically occur as grassy open forests low in the landscape as do red gum systems including E. blakelyi, E. camaldulensis and E. rudis more widely across Australia (Boland et al. 1984). These ecosystems exemplify the interdependence of Aborigines, fire, grassy understoreys and healthy eucalypts that was noted by European explorers and naturalists …………*

- *Other species such as E. deanei, E paniculata, E. propinqua, E. punctata, E. siderophloia and E. smithii, appear to have less site fidelity but are consistently predisposed to decline on difficult sites. Some geological substrates such as Patonga siltstone and the Walloon coal measures reliably indicate these sites. The Wagonga beds and Moruya granites in the Batemans Bay Region, the Wandrawandian siltstones in the Nowra region and the Brooklana, Coramba and Moombil beds at Coffs Harbour require further assessment. Species such as E. dunnii, E. grandis, E. quadrangulata and E. saligna occur on fertile and well structured soils such as krasnozems in the form of wet sclerophyll forests and on poorly structured, drained and aerated soils as naturally grassy forests or woodlands. The wet sclerophyll forests are naturally adapted to high intensity fires at intervals of several centuries and remain healthy over this period whereas the naturally grassy forests are predisposed to decline in the absence of frequent low intensity fire. We speculated that limited areas of E. quadrangulata in Dungog, Wauchope and Bellbrook Regions occur on poorly structured soils. Quaternary alluvium typically indicates difficult sites low in the landscape and all eucalypts that grow on these sites are predisposed to decline.*

There is rapid expansion of eucalypt decline across Australia as noted by Jurskis (2015) in Chapter 12, further detail is outlined in Section 2.3, predisposition factors are changing.

3.5 Importance of low intensity fire to maintain forest health and reduce decline across the landscape

Jurskis (2011 a) highlights the importance of prescribing burning programs:

The patterns and processes described here are in agreement with studies conducted in Tasmania, Western Australia and elsewhere around the globe on the causes of tree decline. These studies show the importance of prescribed burning to the nutrition and health of forests and that nutrient cycles should be an important consideration in planning a healthy fire regime. in Western Australia prescribed burning has been more widely and consistently used with greater public support than in eastern Australia. This research supports extension of burning programs in Western Australia and reinvigoration of programs in eastern Australia. Adaptive management programs are being widely implemented in North America using various combinations of thinning and burning to restore health, resilience and fire safety in ecosystems that have been degraded by exclusion of fire. Similar programs are urgently needed in Australia where various combinations of burning, thinning, grazing and/or slashing could be used on various tenures as appropriate.

Jurskis (2004 d) notes changes in fire and grazing as contributors to decline:

Changes in fire regimes during recent decades have coincided with structural and floristic changes in forests as well as an apparent decline in the health of many types of eucalypt forest. This paper outlines some of the evidence that changes in fire regimes have caused forest health to decline. Long term burning experiments and other comparisons have shown that changes in fire regimes cause changes in soil environments, microclimates, forest structure, flora and fauna. Eucalypt decline is often associated with these changes, and one study identified the underlying processes that are involved. Some agricultural practices produce similar soil environmental changes that cause rural tree decline. Changes in fire and/or grazing regimes appear to be important causes of the widespread eucalypt decline in temperate Australia. Visible contrasts in the health of adjoining stands of forest having different management regimes *suggest that human management overrides other factors, such as climatic stress and the presence of pests or pathogens, in initiating decline.*

Turner and Lambert (2005) also highlight the importance of regular burning:
The level of insects or other folivores is a symptom of the problem and not a primary cause of dieback. Regular burning maintains reasonably stable levels of nitrogen within the system and these levels are the long-term norm for many eucalypt ecosystems. Essentially, lack of regular low-intensity burning can lead to reduced stand health and growth, and, in the longer term, changes in stand structure.

Archibald et al. (2006) recommends a regular burning program in WA Tuart for a range of reasons:

The re-introduction of a regular burning regime in Yalgorup is recommended to limit the potential extent and impact of damage from high intensity fire, reduce understorey competition, promote natural tuart regeneration and restore and/or maintain tall-open tuart woodlands in the landscape.

Such a re-introduction should involve an adaptive management approach whereby trial areas are treated and monitored initially. In areas where little tuart canopy remains, restoration may necessarily involve additional measures including direct seeding or tubestock planting.

It appeared canopy area ratings one year post fire increased as outlined in Figure 1 below.

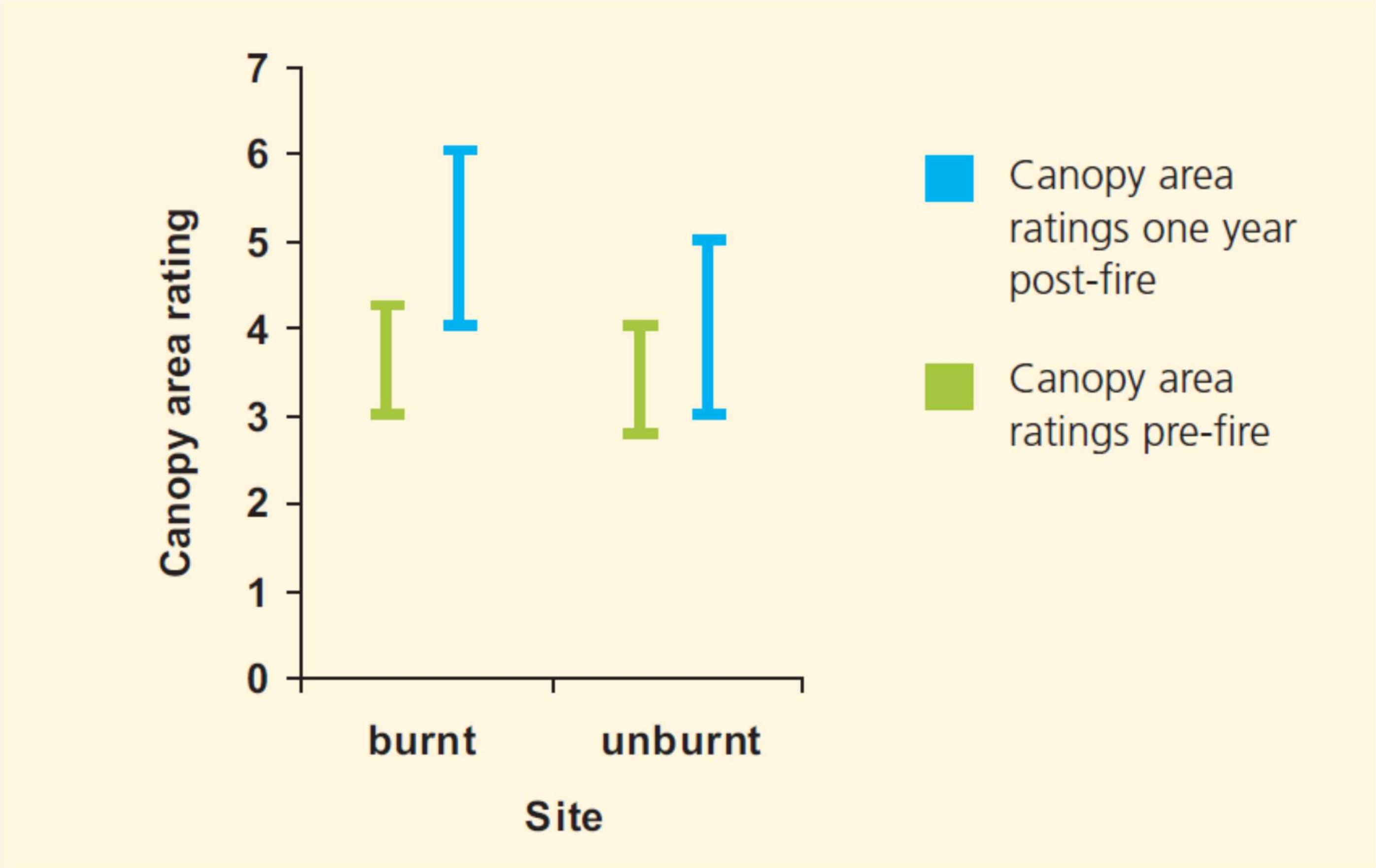


Figure 1. Detail that was extracted from Archibald et al. (2006) Figure (6). Canopy area ratings pre-fire and one year post-fire for tuart trees (< 5 cm trunk diameter) at a controlled burnt site (n = 22) and unburnt site (n = 26) in Yalgorup National Park. The trees at the burnt site with leaf scorch of between 1 and 10 % of total canopy area were selected. Ratings were based on Grimes (1978) with modifications. Interquartile ranges are shown.

3.6 Reasons for a reduction in the extent and frequency of low intensity fire across Australia

Jurskis and Turner (2002) outline a number of reasons for a reduction in the extent and frequency of low-intensity fire in recent decades in SE Australia:

Exclusion of low-intensity fire is increasingly the common land management practice in south-eastern Australia. Reasons for a reduction in the extent and frequency of low-intensity fire in recent decades include:

- *Efficient suppression of fires caused by lightning;*
- *Development of improved pastures for livestock production;*

- *Logistic or aesthetic impediments to burning due to urban, rural residential and 'alternative lifestyle' developments and associated infrastructure;*
- *A desire to protect timber values in regrowth forests by excluding fire;*
- *Regulations that prevent burning in many areas of public forests, for example stream exclusion zones, rare old growth and rare ecosystems (Refshauge et al. 1999); and*
- *A perception amongst some public land managers that a frequent controlled burning regime may reduce biodiversity in forests (….).*

3.7 Changed forest structure and more difficult low intensity fire management and intense wildfires

In the paper Jurskis et al. (2003) and Jurskis et al. (2011), the authors note changes in forest structure is impacting on low intensity burning:

Reduced occurrence of low intensity fire, development of dense shrub layers, and declining forest health are extensive in south eastern Australia (..). The structural changes that are occurring in formerly grassy and open eucalypt forests are reducing the chance that low intensity fires will burn through these forests, making prescribed burning more difficult, and making wildfire control increasingly difficult and dangerous.

Jurskis and Turner (2002) further explain this matter:

Decreased flammability of mesic understoreys following a period of fire exclusion is an important feedback mechanism in mesic dieback …….. Mesic understorey development prevents the ingress of low-intensity fires to these sites. Wildfires that are sufficiently intense to penetrate these sites are likely to cause further damage to the unhealthy eucalypt canopy.

Other valuable information in regards to changed vegetation structure and bushfire risks in SE Australia is included a Tim Lee ABC Landline segment (2021):

"Scientist investigating Australia's past says Indigenous cultural burning key to controlling bushfires". Dr Fletcher's findings are profoundly important for understanding the past. Crucially, they point to how we approach the future.

"We see a shift from an open-forest system to a closed-forest system in all the examples that we've analysed," he said. "Universally, across landscapes that [are] not now farms, we see open forests turning into closed forests" and "In terms of fire, that's a ramping up of fuel levels. "We have really densely stocked forests now that are really high in flammable biomass — that is a real danger."

Hessburg et al. (2005) also examine the issue of dry forests and wildland fires of the inland Northwest USA and also changed forest structure:

Dry forests of the present-day no longer appear or function as they once did. Current patterns of forest structure and composition do not resemble even recent historical conditions, neither do they represent what we would expect to see under or more natural or characteristic disturbance regimes and the current climate. There is little evidence that current patterns are sustainable and this has important ecological consequences.

Large landscapes are increasingly homogeneous in their composition and structure, and the regional landscape is set up for severe, large fire and insect disturbance events. Among ecologists, there is a high degree of concern about how future dry forests will develop and what they will become, if fires continue to be large and severe….

Hagmann et al. (2021) further add to this in relation to western North American forests:

The cumulative results of more than a century of research document a persistent and substantial fire deficit and widespread alterations to ecological structures and functions. These changes are not necessarily apparent at all spatial scales or in all dimensions of fire regimes and forest and nonforest conditions. Nonetheless, loss of the once abundant influence of low- and moderate-severity fires suggests that even the least fire-prone ecosystems may be affected by alteration of the surrounding landscape and, consequently, ecosystem functions. Vegetation spatial patterns in fire-excluded forested landscapes no longer reflect the heterogeneity maintained by interacting fires of active fire regimes. Live and dead vegetation (surface and canopy fuels) is generally more abundant and continuous than before European colonization. As a result, current conditions are more vulnerable to the direct and indirect effects of seasonal and episodic increases in drought and fire, especially under a rapidly warming climate. Long-term fire exclusion and contemporaneous social ecological influences continue to extensively modify seasonally dry forested landscapes. Management that realigns or adapts fire-excluded conditions to seasonal and episodic increases in drought and fire can moderate ecosystem transitions as forests and human communities adapt to changing climatic and disturbance regimes.

4 Lack of low intensity fire, soil factors and eucalypt decline

Fire and soil factors in relation to eucalypt decline are considered in detail in sections 4.1 to 4.11 below.

4.1 The link between fire exclusion from fire dependent systems, soil processes and eucalypt dieback and decline

One paper summarises this issue very well, this being by Jurskis (2011 a) in studies at Eden:

At a long term burning study area, seven adjoining frequently burnt and long unburnt sites were compared in a topographic sequence from upper to lower slope. Two additional sites on a creek flat were also sampled, however there were no repeatedly burnt sites for comparison. A third unpaired, long unburnt site was sampled where there was a dense subcanopy of Allocasuarina littoralis, a nitrogen-fixing species. The repeatedly burnt plots had lower levels of both litter and understorey, and the overstorey trees generally had healthier crowns than in the unburnt plots. On average, unburnt plots had twice as much exchangeable mineral nitrogen and exchangeable aluminium (Al) and lower pH (4.1 in 1:1 water) compared to burnt plots (4.4). The differences between burnt and unburnt plots increased down the slope and the highest levels of nitrogen, aluminium and acidity occurred on the long unburnt creek flats where the mature canopy was dead.

Even higher levels of nitrogen, aluminium and acidity occurred on the same soil type under a long unburnt stand of dead E. consideniana and declining E. globoidea with a dense subcanopy of Allocasuarina littoralis, indicating that development of nitrogen-fixing understoreys can compound the problem of nitrogen accumulation and eucalypt decline in the absence of fire.

The changes in soil condition described here in declining eucalypt forest are similar to those causing decline in many forests and woodlands around the world where high levels of nitrogen may also accumulate as a result of industrial emissions. high levels of nitrogen, aluminium and manganese can be harmful to the roots of eucalypts as has been shown for many other trees around the world. tree declines typically originate in poorly structured soils and affect roots. As the trees weaken, pests, parasites and diseases may attack other parts of the trees. The harmful changes in soil properties may not occur on more fertile, well structured soils such as ferrosols which are better buffered against increasing acidity. These soils support tall, wet eucalypt forests, known as wet sclerophyll forests, which have naturally dense, mesic understoreys and depend on infrequent, high intensity fires for regeneration.

Many burning studies have reported that repeated burning diminishes the nutrient status of forest soils. However Dr Turner emphasises that long-unburnt areas should not be used as experimental controls in dry and moist eucalypt forests which evolved with a regime of repeated low to moderate intensity fires. "Our studies show that repeated burning maintains stable low nutrient conditions suitable for eucalypts". When fire is excluded from dry and moist eucalypt ecosystems, which include about 95 per cent of eucalypt dominated vegetation in Australia, the soil changes can adversely affect established trees and promote woody thickening, allowing a few fire sensitive understorey species to choke out the naturally diverse ground layers.

4.2 Lack of low intensity fire, changes in soils and eucalypt decline, early research

Ellis (1964) observes important factors very early in research in Tasmania:

It appears possible that the death of the eucalypts has followed a radical alteration in the nutrient regime of the soil which may be associated with marked changes in the forest microclimate and the composition of the forest litter. Future work will concentrate on this aspect of the problem.

Ellis et al. (1980) completed a detailed research of Eucalyptus delegatensis high altitude dieback which included felling and burning the understorey in Tasmania. Information in regards to this research is outlined in Section 5.1 and also in Annexure 1. Ellis et al. 1980 paper on Recovery of Eucalyptus delegatensis from high altitude dieback after felling and burning the understorey in Tasmania.

Landsberg (1986) observes:

I hypothesize that the enhanced nutritional quality of the foliage of dieback-affected trees is more likely to be a consequence of benign growing conditions (e.g. improved soil fertility), than of environmental stress. Field data for soil properties and the effect of drought on mature trees are consistent with this view.

Landsberg J (2006) explores this issue and identifies soil fertility as the critical issue:

Canopy dieback of Eucalyptus blakelyi trees is often associated with defoliation by insects: the foliage of trees with dieback is nutritionally superior for insects and is more heavily damaged by them. I investigated whether differences in the nutritional quality of foliage were genetically determined, or caused by environmental stress. In a series of glasshouse experiments, with seedlings and grafted plants derived from dieback and healthy populations of trees. I tested the influence of deprivation of nutrients, drought, waterlogging, saline waterlogging and addition of excess phosphate, on the nutritional quality of foliage. Differences in the foliar properties of plants from different genetic sources were not consistent with the differences between the source populations. Most of the environmental stresses applied caused a reduction in foliar quality (decreased water and nitrogen contents, and increased specific leaf weights). I hypothesize that the enhanced nutritional quality of the foliage of dieback trees is more likely to be a consequence of benign growing conditions (e.g. improved soil fertility) than of environmental stress. Field data for soil properties and the effect of drought on mature trees are consistent with this view.

4.3 Lack of low intensity fire, changes in soils and eucalypt decline, key lead research in NSW

Turner and Lambert (2005) note in their concluding comments:

It is proposed that dieback occurring in east coast eucalypt forests is a result of predisposition to nutritional imbalances. The imbalances are a result of the accumulation of both total and mineral nitrogen within the soil over extended periods of time. The increased nitrogen availability can lead to negative impacts on root and mycorrhizal development and/or biochemical changes within the tree, and this predisposes the trees to insect- and other damage. The changes in nitrogen availability are, in part, a result of understorey development together with differences in nutrient cycling patterns (relatively high quantities of nitrogen in low C:N ratio material) within this component of the ecosystem.

Burning and disturbance due to grazing reduce the impact of the understorey on overstorey health and growth, and also stabilise the pools and availability of nitrogen. Water stress can additionally affect both the availability of nutrients and the accumulation of amino acids, and this results in the trees being vulnerable to insect attack.

At the times that dieback symptoms are apparent on trees, the processes in the soil have been at a stage that may be termed 'negative' for at least ten years, if not longer. Hence, there is a significant lag between a change in soil conditions and dieback becoming obvious in the tree crowns.

The baseline or control is a 'normal' low-intensity fire cycle (3–6 y). Absence of burning is the equivalent of a treatment. Stands affected by dieback but in the final stages may be recoverable, but will probably require three or more fire cycles or the effects of continuous grazing to restructure the understorey and have an impact on soil nitrogen pools before any improvement in the health of the overstorey is observed. Modifications to the understorey (such as mechanical disturbance of weeds) under this model will exacerbate the rate of dieback.

The obvious presence of high insect populations is not the primary cause of dieback but is a result of sick trees sick roots sick soils.

Research by Jurskis, Turner and Lambert in relation to this issue is discussed throughout this document:

- Jurskis (2015).
- Jurskis (2011 a).
- Jurskis (2011 b).
- Jurskis (2005 a).
- Jurskis (2005 b).
- Jurskis (2004 b).
- Jurskis (2003).
- Jurskis et al. (2011).
- Jurskis and Turner (2002)
- Turner and Lambert (2005)
- Refer used key reference list.

4.4 Lack of low intensity fire, changes in soils and eucalypt decline in mainland eastern states, other research

Changes in soil factors in relation to time since burning is explored by Jones and Davidson (2014) in alpine ash in Tasmania:

Absence of fire is increasingly recognized as an important driver of soil nutrient budgets in Eucalyptus forest, especially in forests affected by premature Eucalyptus decline, due to the effects of soil nutrient accumulation on nutrient balances and forest community dynamics. In this study, we present a dataset of soil and foliar nutrient analyses, and vegetation measurements from a fire chronosequence survey in native E. delegatensis forest. Measured indices include total soil and extractable soil nitrogen (N), or phosphorus (P), soil organic carbon (C), soil acid-phosphatase (PME) activity, foliar N and foliar P, and understorey and overstorey vegetation canopy height. We show that in some cases indices are strongly linked to time since fire (2–46 years). Time since fire correlated positively with foliar N, total and extractable soil N, soil organic C, and also soil PME activity; the latter an indicator of biotic P demand. Differences in the strength of these relationships were apparent between two geology types, with stronger relationships on the potentially less-fertile geology. The strong positive correlation with time since fire and understorey canopy height reflected increasing shrub biomass and thickening of the shrub layer. The strong positive correlation for soil or foliar N, but not P, with time since fire, indicates that P does not increase relative to N over time. P may, therefore, become limiting to growth in this plant community. Similarly, the significantly higher concentrations of soil N but not P, also found in both older and long-unburnt forest stands (>100 years since management), may exacerbate a situation of soil nutrient limitation over several decades. A characteristic feature of long unmanaged stands is a developing tea tree (Leptospermum sp.) understorey, which may benefit from elevated soil N availability and increasing organic C accumulation with prolonged fire absence. This increased shrub biomass would outcompete Eucalyptus for resources, including soil nutrients and water.

Granger et al. (1994) further highlight increasing nitrogen associated with declining *Eucalyptus camphora/ E. ovata* stands:

The decline of riparian Eucalyptus camphora/ E. ovata stands is examined in relation to an increase in nitrogen availability and to rising salinity in low-lying areas. There are several indications that declining stands are abnormally rich in N:

(i) Nitrogen availability in declining stands was greater than that recorded in other Australian forests, was dominated by nitrification and was extremely variable.
(ii) Nitrate concentrations in free soil water from declining forest on a dry site were many times those in the corresponding healthy forest.
(iii) N/Mg ratios in foliage of declining trees on drier sites were at the extreme end of the recorded range and similar to those found in eucalypt plantations on agricultural soils.
In addition, sites where the overstorey eucalypts are declining have been invaded by a variety of herbaceous weeds, most of which display characteristics of nitrophilous plants, e.g. nitrate reductase activity was greater in herbaceous weeds than in native overstorey or understory species in declining stands of E. camphora/ E. ovata and was directly related to the concentration of nitrogen in foliage. These observations are consistent with recent suggestions that forest ecosystems may become N-saturated.

4.5 Lack of low intensity fire, changes in soils and eucalypt decline in Western Australia

Ishaq (2014*)* highlights research in relation to E gomphocephala decline in WA:

Some soil abiotic factors might be involved in the tree decline syndrome, and a number of soil chemical properties analysed were significantly related to E. gomphocephala decline. The study found that there was a positive relationship between tree health and soil pH (CaCl2). Eucalyptus gomphocephala is largely confined to calcareous soil profiles, so it is possible that a decrease in soil pH may be a factor predisposing trees to decline.

Furthermore, an imbalance in mineral nutrients may also play a role in the health of E. gomphocephala, predisposing trees to decline. The study found that crown health of E. gomphocephala was positively related to the micronutrients Mn, Cu and Zn.

Whether the decline of E. gomphocephala is directly affected by change in soil chemistry or the decline is related to mycorrhizal fungi mediated by change in soil chemistry is not known. However, it is evident that altered soil chemistry can result in stress.

Close et al. (2011) also outline research in relation to E gomphocephala decline in WA:

The objective of this study was to investigate how the management practices of prescribed fire and understorey vegetation removal affect water and nutrient relations of old, yet prematurely declining Eucalyptus gomphocephala. Long unburnt sites were established in Yalgorup National Park, Western Australia, adjacent to frequently burnt state forest sites. Trees were allocated to vegetation clearing, prescribed fire or no prescribed fire treatments. Prescribed fire was achieved in only one long unburnt national park site so that the results were pseudoreplicated but analysed accordingly. Soil chemistry, plant nutrient availability and tree foliar carbon and nitrogen isotope ratio and nutrient concentration were investigated. No effects of vegetation clearing were found. Prescribed fire sites were associated with sky exposure and bare ground whereas no prescribed fire sites were associated with shrub and litter cover and litter depth. Foliar carbon isotope ratios were significantly more negative in prescribed fire, relative to no prescribed fire, treatments on long unburnt sites. Soil exchangeable Zn and Mn and plant available (estimated by charged resin beads) Mg were higher on prescribed fire, relative to no prescribed fire, long unburnt sites. Seedling bioassays indicated elevated P and Cu availability on prescribed fire, relative to no prescribed fire, treatments. In overstorey E. gomphocephala, foliar N levels were elevated (but not to excessive levels), and there was a trend toward elevated foliar Mn, in prescribed fire relative to no prescribed fire treatments on long unburnt sites. In the context of our large scale pseudoreplicated case study, prescribed fire provided a pulse of water and N, (with some indications towards provision of elevated Mn, Cu and Mg) availability to E. gomphocephala in decline on sites with a history of a long absence of fire that may in part underpin observations of elevated tree health on sites that have a history of relatively frequent fire.

Close et al. (2009) includes a good discussion in relation to Tree Nutrient-Availability:

- N Cycling
- P cycling
- Soil pH and Exchangeable Cations

Barber et al. (2007) have also completed research in relation to E gomphocephala decline in WA:

………..preliminary work has indicated that in the year after a fire, crown vigour increased for trees lightly scorched by fire (< 10% of the canopy) compared to trees in an adjacent unburnt area. Findings have also confirmed the anecdotal

reports that the survival and growth rate of E. gomphocephala is significantly greater on artificial ashbeds than off. Comparison of the foliar nutrient concentrations observed in E. gomphocephala with those published for other eucalypts, shows levels of Zn and N that are particularly low in E. gomphocephala and these low levels tend to be more common in trees in the Yalgorup region, where canopy decline is severe. The application of a Zinc treatment or a Complete Nutrient treatment (containing N, P, K, Zn, Mn, Fe) stimulates canopy recovery, suggesting that Zn and other unidentified nutrients are limiting the growth of these trees. Trees injected with Fe alone and control trees slightly declined in health over a 12 month period while trees injected with Zn or a Complete Nutrient in combination with low rates of potassium phosphonate (25g/L & 50g/L) showed a good response. Recent soil analyses have shown a strong correlation between a particular functional group of bacteria and crown decline of E. gomphocephala.

4.6 Forest decline and changes in plant nutrient availability and content across the world

Dijkstra and Adams (2015) highlight findings from a fire and nitrogen/ phosphorus study of woody plant systems across the world, narrowed down to locations 54 publications used in the meta-analysis:

Fires are widespread and can result in large nutrient losses from ecosystems simultaneous with pulses in nitrogen (N) and phosphorus (P) that can increase their availability to plants. Plant growth is frequently limited by N and P, and fire has the potential to enhance or moderate the magnitude of N and P limitation in plants with important consequences for long-term net primary productivity and global carbon cycling. We used meta-analysis to explore fire effects on N and P concentrations in aboveground plant biomass among a variety of plants and plant communities worldwide. We show that across all observations, fire enhanced N concentration in plants when N/P ratios in biomass were low, and enhanced P concentration in plants when biomass N/P ratios were high. P concentration increased particularly in woody plants. Furthermore, responses of the N/P ratio in woody plants were more flexible than in herbaceous plants so that fire eased N and P imbalances only in woody plants. Our results suggest that these changes in plant N and P in response to fire may help sustain net primary productivity and persistence of woody plants in fire-affected ecosystems worldwide.

Other findings of Dijkstra and Adams (2015) include:

- *Because of a lack of long-term observations, we were only able to reliably analyze short-term effects of fire on plant [N] and [P] (observations less than 4 years since the fire event).*
- *Our meta-analysis supports our hypothesis that at the global scale and in the short-term, fire is important for improving plant [N] and [P] thereby potentially reducing constraints on plant growth. Plant [N] and [P] increased in response to fire across a wide range of N/P ratios in unburned herbaceous plants (on average by 11 and 12 % for N and P, respectively, across all three N/P categories), but plant [P] showed the largest increases in response to fire in woody plants (by 85 %) when unburned plant N/P ratios were larger than 20 (implying N sufficiency, and possibly limitation by P or other nutrients). These results suggest that fire may be particularly important for easing P constraints of growth of woody plants in P poor systems.*
- *Plant [N] and [P] were not related to available pools of N and P in the soil, suggesting that fire effects on available soil N and P are poor predictors for plant responses. It should be noted, however, that available forms of N and P in the soil were determined with different extraction methods. Therefore, effect sizes may have been influenced by the extraction method used, and this may have obscured relationships with plant [N] and [P]. Further, increased supply of N and P in the soil does not necessarily increase plant [N] and [P], but may only stimulate plant growth. Nevertheless, fire increased both available soil N and P. These increases could have been a result of increased supply of N and P directly after fire, but also because of reduced uptake due to a reduction in plant biomass directly after fire.*
- *The majority of studies were prescribed burns that tend to be less intense than wildfires or slash- and-burn fires, which may have influenced our results. However, there were no significant differences in plant [N], [P], and N/P responses among fire types, whereas fire effects on plant [N] and [P] were significant for all three fire types (Table 1) suggesting that our results are broadly applicable.*
- *The data presented … highlight that as N and P become more limiting to plant growth, so does the importance of fire to relieving that limitation, particularly for woody plants.*

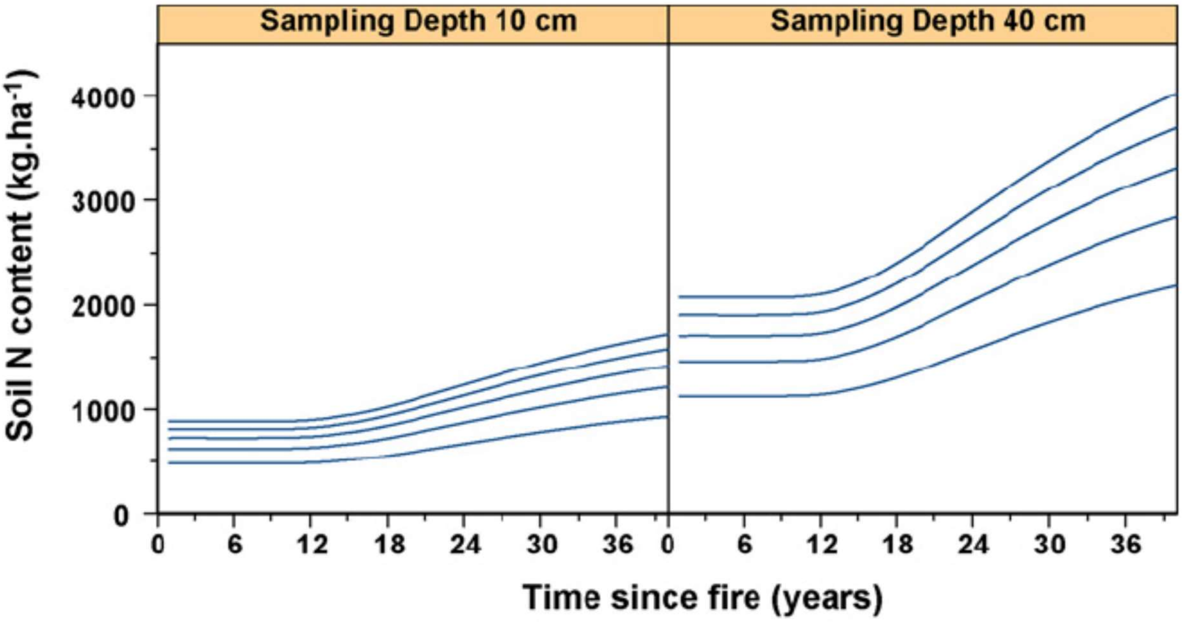
4.7 Soil and tree health change over time

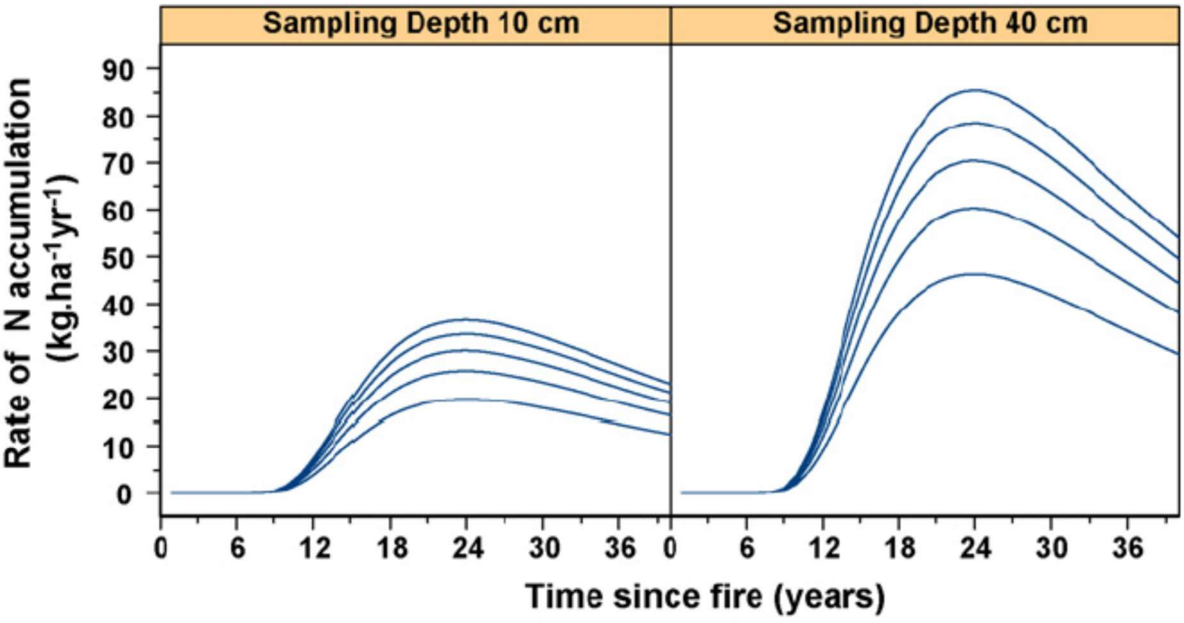
Important points noted in Turner et al. (2008):

- *Nitrogen appears to increase in quantity in the soil with time since fire, and the rate of increase is related in part to the basic soil fertility as indicated by soil phosphorus levels. The apparent rate of increase in the surface soils is approximately 11– 21 kg N ha1 year1 with the potential for higher levels on more fertile soils. The source of the N is assumed to primarily be N fixation, as the measured atmospheric inputs were of the order of 1 kg ha1 year1.*
- *The increases in N lead to a reduced soil C/N ratio, higher N mineralisation and reduced pH. It is proposed that the reduced pH is a result of a combination of nitrification, related to the increased soil N, and a reduction in base cations through uptake by vegetation.*

- *It is hypothesised that these changes create a poorer root environment and nutritional status for eucalypts, and these changed conditions can impact directly on tree health and increasing susceptibility to pests and pathogens.*
- *In the subsidiary study of paired plots found there was declining tree health in the long unburnt areas related to changes in soil characteristics, compared with the adjacent regularly burnt areas.*

Soil N content was relatively stable for the first 10 years after fire and then increased with time (Fig. 3). As time goes to infinity, the asymptotic maximum of soil N content ranges between 1299 and 2395 kg ha1 for the surface soil and between 3043 and 5610 kg ha1 for the deeper soil across the five levels of soil fertility in Fig. 3. The rate of N accumulation appeared to peak at 24 years after fire then decreased afterwards (Fig. 3). Correspondingly, C/N ratio changed little for the first 10 years after fire and then decreased with time. As time goes to infinity, the asymptotic minimum of C/N ratio ranges from 15.83 to 17.25 for the surface soil and from 14.81 to 16.14 for the deeper soil across the five levels of soil fertility in Fig. 3. (Note extracted Figure 2 below).


Sampling Depth 10 cm
Sampling Depth 40 cm
Soil N content (kg.ha^{-1})
4000
3000
2000
1000
0
0
6
12
18
24
30
36
0
6
12
18
24
30
36
Time since fire (years)


Sampling Depth 10 cm
Sampling Depth 40 cm
Rate of N accumulation (kg.ha^{-1}yr^{-1})
90
80
70
60
50
40
30
20
10
0
0
6
12
18
24
30
36
0
6
12
18
24
30
36
Time since fire (years)

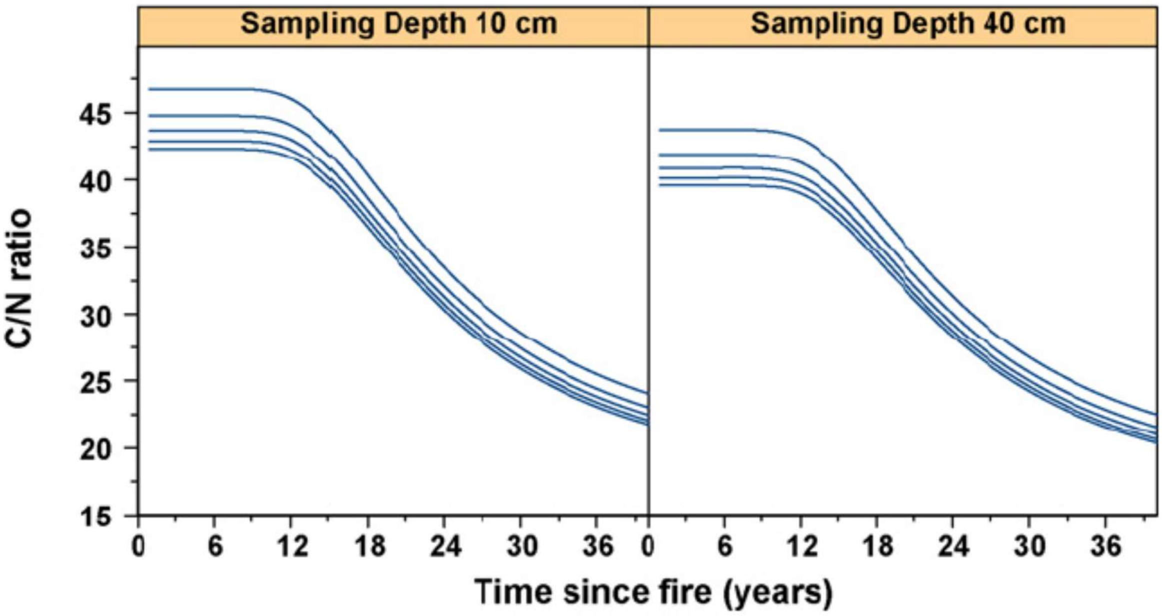

Sampling Depth 10 cm
Sampling Depth 40 cm
C/N ratio
45
40
35
30
25
20
15
0
6
12
18
24
30
36
0
6
12
18
24
30
36
Time since fire (years)

Figure 2. Detail from the Figure (3) that was extracted from Turner et al. (2008). Soil N content, rate of N accumulation and C/N ratio in relation to time since fire across five levels of total P of surface soil at 20, 40, 60, 80, 100 kg ha1. The five curves in each panel represent increasing levels of soil fertility from bottom up for soil N content and rate of N accumulation, and conversely for C/N ratio.

More detail is provided below in Figure 3:

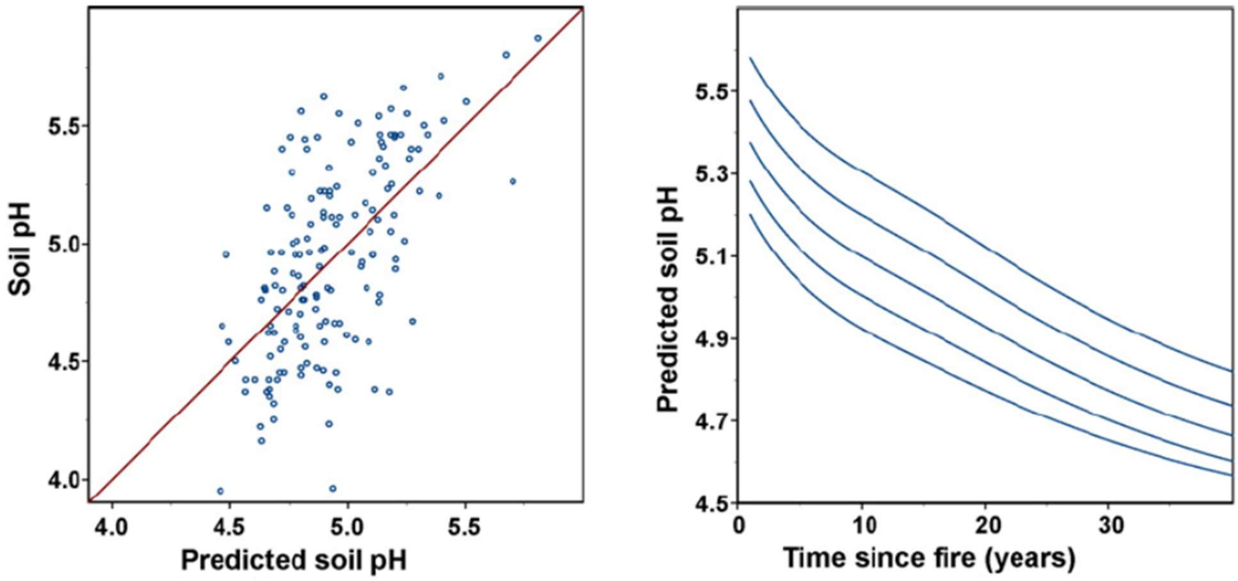


Figure 3. Detail from the Figure (4) that was extracted from Turner et al. (2008). Observed and predicted values of soil pH with a diagonal line of unity (left), and predicted changes of soil pH with time since fire (right) across five levels of total P of surface soil at 20, 40, 60, 80, 100 kg ha1 from bottom up.

Turner et al. (2008) points out important information:

- *The asymptotic minimum of soil pH ranges from 4.32 to 4.47 across the five levels of soil fertility as time goes to infinity (Fig. 4).* (Note this is Figure 3 above).
- *The changes in pH indicated a declining trend representing approximately one pH unit over the period of the study (Fig. 4).*

4.8 Stages in nutrient availability with eucalyptus dieback and decline

Turner and Lambert (2005) identify three stages from the commencement of the stand establishment:

Stage 1. Nitrogen losses (uptake) are greater than inputs, leading to a net decline in soil nitrogen. The decline in nitrogen may be in conjunction with a decline in carbon and/or an increasing C:N ratio.

Stage 2. Uptake declines and inputs become greater than outputs. Soil nitrogen and carbon accumulate. In the absence of fire, the nitrogen content reaches the initial level. Mineral nitrogen (NH 4+ and NO3–) increases while the C:N ratio declines. Regular burning minimises the process.

Stage 3. Nitrogen accumulation increases in the soil with large increases in mineral nitrogen leading to nitrogen saturation. The C:N ratio declines and may be 20 or less (e.g. in E. regnans as reported by Polglase et al. 1986). Forests either tolerate or utilise the mineral nitrogen (particularly nitrate), such as in rainforests and mountain ash (E. regnans), or they degenerate. At this stage, stands are losing nitrate through leaching and it can be measured in soil and runoff water.

Two aspects need to be considered. First, Stage 2 is the main stage where the presence of fire leads to a fluctuating equilibrium in soil nitrogen; and second, soils naturally low in nitrogen will rapidly reach saturation with related forest declines, whereas fertile soils (such as those derived from basalts) are strongly buffered and many species have adjusted to utilising high mineral nitrogen.

4.9 Lack of low intensity fire, changed ectomycorrhizal communities mediated by soil chemistry and eucalypt decline, early research

Ellis and Pennington (1992) highlight some critical findings in relation to changes in soil microbiological factors, and specifically in relation to mycorrhizal associations and dieback:

In many highland forests of Eucalyptus delegatensis in Tasmania the establishment and healthy growth of eucalypts is promoted and maintained by fire. In the absence of fire, secondary succession from eucalypt forest to rainforest occurs, during which the eucalypts decline and die prematurely. On sites that are prone to radiation frost severe reduction or removal of a tree canopy allows a sward of tussock grasses to develop, in competition with which seedlings of eucalypts decline in growth and a high proportion dies.

Factors of the soil that could contribute to these phenomena were investigated by means of pot experiments that used soils from: 1) a secondary succession of vegetative types from recently burned healthy eucalypt forest to unburned mature rainforest: this encompassed a sequence of decline and death of the eucalypt trees; 2) soil from old grassland in which eucalypt seedlings were exhibiting severe growth check and mortality; 3) from beneath individual trees of several species growing on old grassland.

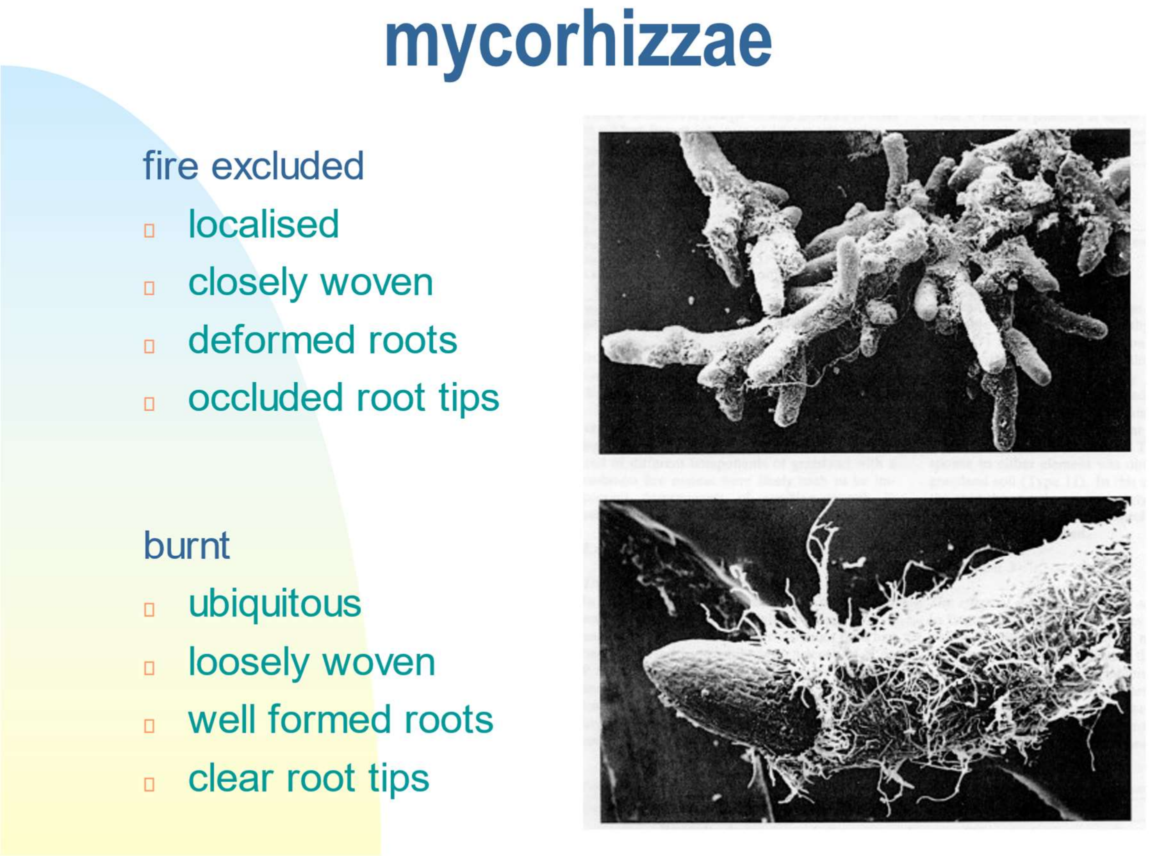
Growth of seedlings in untreated pot soil reflected closely the condition of eucalypt trees in the field in that growth declined through the successional sequence to rainforest; it was very poor in soil from old grassland; and it varied markedly among soils from beneath different tree species and phases of the grassland. Mycorrhizal development on the pot seedlings differed among soils in both forms and associated fungal types.

Poor growth was overcome only partially by either addition of N and P fertilisers or by partial sterilisation of soil by using steam or chemicals. Inoculation of inhibitory soil from both secondary rainforest and old grassland with 10% to 20% of soil from a healthy eucalypt stand overcame inhibition completely in each case. It is concluded that changes in soil microbiological factors, and specifically in mycorrhizal associations, that accompany changes in vegetative components of the eucalypt stands could be the principal cause of both dieback of older trees and growth check of seedlings.

4.10 Maintenance, fire, changed ectomycorrhizal communities mediated by soil chemistry and eucalypt decline, more recent research

Jurskis (2004 d) outline that high levels of nitrogen in soils can: inhibit mycorrhizae, stimulate microbes (including phytophthora) that are antagonistic or pathogenic towards trees and elevate protein levels in the sap and leaves of trees, making them more favourable to pests and pathogens.

Jurskis (2004 c) highlights detail in relation to mycorrhizae:



mycorhizzae

fire excluded
- localised
- closely woven
- deformed roots
- occluded root tips

burnt
- ubiquitous
- loosely woven
- well formed roots
- clear root tips

Figure 4. Detail that was extracted from Jurskis (2004 c) in relation to mycorrhizae.

Horton et al. (2013) undertook an innovative study with major findings in relation to ectomycorrhizal fungi in Tasmania:

Eucalypt forest decline has a complex aetiology often linked to altered soil chemistry caused by environmental disturbances. Forest decline has also been linked to alterations in ectomycorrhizal (ECM) fungal communities, which are imperative for nutrient transfer and affect ecosystem productivity and health. Our aim was to determine the influence of soil chemistry on ECM fungal communities and tree health in declining temperate eucalypt forests. We hypothesise that forests with changed soil chemistry, in particular altered nitrogen cycling associated with forest decline, supports unique ECM fungal communities. ECM communities from twelve Eucalyptus delegatensis forest plots were characterised by DNA sequencing of root tip and sporocarp samples. Tree health and nutrient concentrations from soil and foliage samples were quantified for each plot. Multivariate and regression analyses and t-tests were used to determine ECM fungal community differences between forest health classes, and identify which soil variables were important for defining these communities. Elevated available soil nitrogen and soil acidity were associated with severely declining forest. Soil pH, nitrate and organic carbon significantly explained the majority of variation in ECM fungal community composition and structure, which differed between moderately and severely declining forest. Russulaceae species richness was greatest in acidic soils (severely declining forest) while Cortinariaceae species richness was greatest in soils with lower concentrations of soil nitrate (moderately declining forest). Total ECM fungal richness was inversely related to available soil phosphorus and soil nitrate. Thus, altered soil chemistry associated with eucalypt forest decline mediates changes in the ECM fungal community. Forest management must consider the role of disturbance in maintaining suitable soil conditions for symbiotic fungi which are important for maintaining healthy eucalypt forest and restoring declining forest ecosystems.

Conclusions

This study of eucalypt forest decline is the first to investigate the link between ECM fungal community attributes and health of the forest trees. In the absence of disturbance such as fire, N accumulates to a level where nitrification occurs, and pH decreases. P availability is reduced along with a substantial reduction in P uptake, reflected in the higher foliar N:P ratios. Under these conditions (a shift to P limitation from N limitation) eucalypts may lose their competitive advantage leading to altered vegetation community composition, explaining the tendency for forest with a rainforest understory to exhibit more severe decline symptoms. The ECM fungal communities of E. delegatensis forests play an important role in this eucalypt forest decline process, responding to changes in soil chemistry (increased N and declining P and pH). Shifts in ECM fungal community composition and structure as a result of altered soil chemistry under conditions of forest decline include a reduction in Cortinariaceae diversity, increases in Russulaceae species and a decrease in overall ECM species richness. These changes impact on ecosystem function and tree health, and ultimately affect plant performance. Tree nutrient acquisition could be reduced (i.e. P uptake) due to these shifts in ECM fungal communities and associated altered functions. Particular species and assemblages of ECM species may be better adapted to cope with ecosystem changes associated with eucalypt decline (e.g. the Cortinariaceae or Russulaceae which were related to different level of forest decline and soil chemistry) and could be important for the recovery of these forests.

Ishaq (2014) highlight WA research in relation to Tuart decline and ECM and AM fungi:

The most important finding of the study was the relationship between the type of mycorrhiza (arbuscular or ectomycorrhizal) formed in containerised seedlings and the crown condition of E. gomphocephala at the sites where the soil cores were taken. Ectomycorrhizas were relatively abundant in seedlings grown in soils taken from under healthy crowns, and positively related to the crown condition of E. gomphocephala in the field. By contrast, arbuscular mycorrhizas were abundant in seedlings grown in soils taken from under declining crowns, and this was negatively related to the crown condition of E. gomphocephala. This finding was consistent throughout the study, and confirmed in a second glasshouse trial using soil collected from one healthy and one declining site. Furthermore, molecular analysis used to evaluate fungal communities associated with seedling roots from the bioassay trial showed similar trends with ECM fungi being dominant and diverse for seedling roots grown in soil collected from healthy sites, whilst the AM fungi dominated the seedling roots grown in soil collected from declining sites.

Ishaq et al. (2018) provide further detail on WA research in relation to Tuart decline and fungi:

We used molecular profiling with 454 pyrosequencing to identify ectomycorrhizal, arbuscular mycorrhizal fungi, and other fungal communities associated with containerized Eucalyptus gomphocephala seedling roots. We found a higher proportion of ectomycorrizal fungi associated with seedling roots grown in soil collected from sites with healthy trees, and of arbuscular mycorrhizal fungi from seedling roots grown in soil collected from sites with declining trees. We also found a relatively high proportion of pathogenic fungi present in roots from declining sites compared to healthy sites..

Scott et al. (2013) provides further detail on WA studies in the Tuart decline and fungi:

The fine roots and ectomycorrhizae system of 18 declining Eucalyptus gomphocephala trees, in the Yalgorup region, approximately 100 km south of Perth, Western Australia, were exposed using an air spade and the relationships between the crown health and the fine root and ectomycorrhizal total density scores (TDS) were determined. Crown health was significantly correlated with the fine root and ectomycorrhizal TDS and trees with crown decline symptoms had significantly fewer fine roots and ectomycorrhizae than trees with healthy crowns. In addition, E. gomphocephala *seedlings were grown in-situ within the exposed fine root mats adjacent to the 18 woodland trees and the relationships between seedling and tree health was assessed. Seedling survival, height and foliar health were significantly correlated with the crown health of the adjacent woodland trees. Seedling survival was also significantly correlated with the ectomycorrhizal TDS of the adjacent woodland trees. The relationships between reduced seedling health and reduced crown health and ectomycorrhizal density of the woodland trees indicates that decline symptoms may be associated with the absence of ectomycorrhizae. The study demonstrates new techniques for assessing the fine root and ectomycorrhizal densities of large woodland trees and their relationships to crown health.*

Scott et al. (2013) outlines further detail on WA research in relation to Tuart decline and Phytophthora disease:

The improvement in the crown health of E. gomphocephala trees following trunk injection with phosphite at concentrations of 75 g/L or 150 g/L is strong evidence that Phytophthora pathogens have contributed to the decline in E. gomphocephala CHS.

4.11 Changed ectomycorrhizal communities and forest decline in other countries

Phillips et al. (2013) highlight points in relation to differences in mycorrhizal fungi:

- *ECM fungi are a diverse group of fungi from multiple phylogenetic groups – nearly all of which associate with trees. These facultative plant associates form a thick mantle around root tips from which clusters of hyphae (mycelium) extend beyond the root zone (e.g. as rhizomorphs) and turn over slowly relative to AM hyphae (e.g. months to years). (References listed in Phillips et al. (2013)*
- *Arbuscular mycorrhizal fungi are a monophyletic, species-poor group of fungi which associate obligately with c. 80% of all land plants – most of which are grasses. While it is well-known that these fungi enhance plant phosphorus (P) acquisition by extending hyphae beyond the nutrient depletion zones around roots, their role in acquiring N – the primary limiting nutrient in most temperate ecosystems – has only recently been recognized AM hyphae rapidly colonize soil patches rich in organic N and take up and transport both inorganic and organic N forms. Given that most AM fungi have limited saprotrophic abilities and inorganic N forms are relatively mobile in soils where AM plants are dominant, it is believed that these plants primarily utilize inorganic N forms. (References listed in Phillips et al. (2013).*

Castano et al. (2019) provide further detail:

- *Soil microbes are essential components of forest ecosystems. Among soil fungi, mycorrhizal species are especially important because they form a beneficial symbiotic association with plants, providing them nutrients in return for photosynthetically fixed carbon (C). Ectomycorrhizal (ECM) fungi are also key players in the alleviation of drought stress for trees, and the role of these organisms is especially relevant for nutrient uptake by plants under nutrient-limited conditions (….). Arbuscular mycorrhizal (AM) species are also efficient in uptake and transfer nutrients, especially phosphorus.* (References available in Castano et al. (2019))
- *Eucalyptus tree species have dual mode of mycorrhizal symbiosis, with both ECM and AM taxa, although association with AM species seems to be restricted to seedlings or younger trees. Changes in soil chemistry, fertility or host tree status may change the balance of such mycorrhizal associations. For example, depletion of inorganic soil N could negatively affect AM taxa due to their preference for inorganic N forms, although evidence of access of AM fungi to organic sources has been shown. ECM fungi are especially adapted to mobilize N from organic forms through oxidation chemistry. Studies on Eucalyptus plantations' impacts on the surrounding environment have neglected the soil microbial communities, especially saprotrophs. Saprotrophic fungi have a paramount role in litter and SOM degradation. Understanding soil fungal community structure and functioning in forest ecosystems is important, because these fungi determine many important ecosystem processes….. (References available in Castano et al. (2019))*

Eagar et al. (2022) highlight:
Trees associating with different mycorrhizas often differ in their effects on litter decomposition, nutrient cycling, soil organic matter (SOM) dynamics, and plant-soil interactions. For example, due to differences between arbuscular mycorrhizal (AM) and ectomycorrhizal (ECM) tree leaf and root traits, ECM-associated soil has lower rates of C and N cycling and lower N availability than AM-associated soil. These observations suggest that many groups of nonmycorrhizal fungi should be affected by the mycorrhizal associations of dominant trees through controls on nutrient availability.

Marañón-Jiménez et al. (2022) note:
Intensification of droughts may aggravate the generally low capacity of Mediterranean soils to store C and nutrients and induce soil C:N:P stoichiometric imbalances through its impact on soil microbial biomass and activity. Soil microbes may nonetheless have different responses to seasonal and chronic drought, but very few studies investigate long-term drought periods under field conditions. This study compares the effects of seasonal drought versus the impacts of 16 years of chronic experimental drought on microbial biomass and nutrients and assess the implications for soil nutrient availability and biogeochemical functioning in a Mediterranean forest. The chronic drought treatment reduced substantially and persistently microbial biomass C, N and particularly P, probably due to P-sparing

community shifts or microbial adaptations. The smaller microbial N pool and lower mineralization activity contributed to the accumulation of C- and N-rich organic compounds in the soil and to a lower availability of mineralized forms of N during the vegetation growing season. As a result, chronic drought conditions may increase the risks of N losses from the plant- soil system in Mediterranean ecosystems. Microbial C:N ratios remained unaltered under chronic drought compared to control, likely associated with the equivalent accumulation of C- and N-rich osmolytes by microbial communities. In contrast, microbial biomass increased its C content relative to N content in response to seasonal drought, but also reduced considerably its N and P pool. Therefore, while microbial P was more sensitive to chronic water stress, microbial N and C were more closely coupled to the seasonal fluctuations of water availability.

Highlights

- *Chronic drought reduced microbial C, N and P storage, but C:N ratios were unaltered.*
- *Microbial P was more sensible to chronic water stress than microbial N and C.*
- *Chronic drought impaired the capacity of microbes to regulate soil N availability.*
- *Seasonal drought reduced microbial N and P, but not C storage, so C:N ratios rose.*
- *Microbial N and C varied with seasonal fluctuations of water availability*

5 Other issues in relation to lack of low intensity fire and eucalypt decline

Other issues in relation to eucalypt decline is considered in detail in sections 5.1 to 5.5 below.

5.1 Important growth and understorey research in Tasmania by Ellis et al.

Ellis et al. (1980) completed a detailed research of Eucalyptus delegatensis high altitude dieback which included felling and burning the understorey in Tasmania. Information in regards to this research is outlined below and also in Annexure 1 Ellis et al. 1980 paper on Recovery of Eucalyptus delegatensis from high altitude dieback after felling and burning the understorey in Tasmania. This research is summarised below:

Summary
The following four treatments were applied to each of four stands of alpine ash E. delegatensis (R. T. Baker) in Tasmania that were suffering differing degrees of high altitude dieback: (a)felling the understorey only, (b)felling the understorey and burning once, (c)felling the understorey and burning periodically, and (d) untreated control. Simply felling the understorey did not lead to improved growth and at first appeared to diminish growth on one plot. Felling and burning the understorey resulted in an improvement in the rate of growth of badly affected trees by 75 percent over a period of 12 years: less affected trees showed smaller relative responses. Periodic controlled burning of the understorey could prove to be a practicable means of maintaining, in good health, stands of alpine ash growing at high altitude.

Growth in Diameter
Between 1963/1964 and 1976, trees on the burned plots in each of the North, South, and West Blocks grew at a significantly faster rate than those on the control or felled-only plots. Furthermore, the rate of growth in the control plots of each block was found to be inversely related to intensity of dieback (Table 1). In contrast, the relative stimulation to growth attributable to burning was greater the greater the initial intensity of dieback (Table 2).

The ratios of mean annual rates of growth on treated and control plots in 1963/64-71 and 1971-76 indicate that the stimulation to growth effected by the single burn was maintained during both periods.

Discussion

The results of the felled-only treatment indicate that competition for moisture or nutrients by the living understorey is probably not an important factor in dieback. Rather, the factors responsible may be associated with the accumulation of organic debris on the forest floor and in the upper horizons of the soil profile. It is of interest that removal of this debris by fire on the burned plots is associated with the prompt establishment of healthy regrowth. On the felled-only plots, regrowth became established several years after treatment probably after profound changes had occurred in the forest floor. This suggests again that inhibitory factors may be present in the unameliorated soils of the stands.

It is possible that high altitude dieback in Tasmania is related to the phenomenon of soil sickness. In discussing this in an agronomic context……. In an earlier paper (….) it was reported that, at a depth of 10 cm, mean summer soil temperatures were as much as 5 degrees C higher under healthy stands than under those suffering dieback; comparable maximum summer temperatures differed by as much as 8 degrees C. Felling and burning the understorey led to an increase in mean summer temperature of about 5 degrees C at a depth of 10 cm, and this represents a relatively large change in the soil's environment.

and:

To conclude, when the understories of stands suffering from a range of intensities of dieback were felled and burned the relative response in growth of the eucalypts was found to increase with the initial intensity of the dieback. Burning stimulated the rates of growth of affected stands until they approached that of an apparently healthy stand and the effect has been maintained for 12 years. Thus periodic controlled burning that removes the understorey should prove to be a practicable means of maintaining, in good health, stands of alpine ash growing at high altitude.

5.2 Fire and understorey biomass and nutrients

Grove and Malajczuk (1985) highlight research into the of understory biomass and nutrient contents in karri stands in WA:

Nutrient composition of aboveground components of overstorey trees and understorey shrubs were measured in four even-aged stands of E. diversicolor (4-, 8-, 11- and 36-years-old) and in a mature stand. The even-aged stands had regenerated from seed after cleafelling and slash-burning of native forest, and understories in the younger stands were the same age as trees. However in the 36-year-old and mature stands understories had regenerated from seed after prescribed burning and were 9 and 14 years of age, respectively. Trymalium spathulatum and the legume Bossiaea laidlawiana were the dominant understorey species in all stands.

Aboveground nutrient pools varied less than biomass with stand age. This is because much of the increase in biomass as stands develop is due to production of heartwood, in which concentrations of nutrients are low.

Understories contained a large proportion of the nutrients in all stands. In the 8- and 11-year-old stands about 46% of the aboveground biomass was understorey and this contained 49–56% of the N and S. In the 36-year-old stand, understorey contained 35% of the N and S although it was only 10% of the aboveground biomass. There was relatively more of the nutrient elements other than N and S in E. diversicolor than in understorey species in the 4-, 8-, and 11-year-old stands.

In all five stands B. laidlawiana was an important component of the understorey, amounting to 51–93% of the biomass and containing 72–97% of the N. The leaves of B. laidlawiana contained about 40% of the P, and 31–36% of the N, S, Mg, Zn and Mn but comprised only 6–8% of the aboveground weight.

Jurskis (2012) raises important points in regards to the concern with treating symptoms and contributors rather than causes of environmental degradation forests:

Native or exotic woody plants can proliferate in dry and moist eucalypt ecosystems shading out many other native species, contributing to chronic decline of eucalypts and reinforcing unnatural fire regimes and nutrient cycling processes. Whether native or exotic, they proliferate as a consequence of disturbances which impact directly on these ecosystems. The most extensive ongoing disturbance since European occupation of Australia has been the disruption of frequent mild burning by humans. This burning maintained dynamically stable nutrient cycling processes and a competitive balance in dry and moist eucalypt systems and prevented plant "invasions".

Rose (1997) highlights research in Sydney in relation to understorey density:

Suburban edges are shown to exert a major influence on invasion of the native Pittosporum undulatum Vent, in dry sclerophyll bushland of northern Sydney. Transect data from fifteen urban bushland sites spanning approximately 90 years of development indicate significant increases of P. undulatum with time. Basal area, density and frequencies of plants in all size-classes increased significantly with age of adjoining development. Mean basal area at edges of old sites was 5700 times greater than in comparable bushland in larger reserve interiors. The effect of age was compounded by the greater impact of edge effects in narrower reserves of older suburbs. Basal areas and proportion of reproductive plants decreased significantly with distance into the reserve. Older sites contained larger but fewer individuals at the edge, compared with high densities of smaller plants further into the reserve, suggesting an advanced successional stage.

Gleadow and Ashton (1981) note that increasing understorey Pittosporum undulatum suppresses the original sclerophyllous understorey:

Pittosporum undulatum is invading eucalypt open forests in south-central Victoria, 200 km west of its native habitat in eastern Australia. This is due to horticultural plantings of P. undulatum and to the suppression of wildfires: it has thin bark and is killed by fires which most eucalypts can survive. Near Melbourne, P. undulatum preferentially establishes around the butts of eucalypts and other established trees although in denser forests this clumping is not so obvious. Seedlings of other weed species such as Ilex aquifolium and Cotoneaster pannosa similarly aggregate around established shrubs and trees. Classification of quadrats by monothetic division showed P. undulatum to be the most important species in the community. The weedy nature of P. undulatum is clear from its rapid dispersal, early seed production and fast growth. The dense canopy dramatically reduces the light intensity and completely suppresses the original sclerophyllous understorey: only Gahnia radula remains. Soil beneath the canopy is fertile and the litter is high *in nutrients but bioassays indicate that inhibitors may be present. The root system is variable, depending on soil texture and compaction. The invasion of forest remnants by P. undulatum and other weeds is threatening the survival of the eucalypt forests in urban areas.*

5.3 Fire, forest decline, structure decline, mesophication and changes in soil temperature, dampness and light in Australia

Ellis (1971) undertook research in relation to dieback of alpine ash as related to changes in soil temperature:

A widespread mortality of alpine ash, Eucalyptus delegatensis (R.T. Baker), in northern Tasmania is considered to be due to changes in the microclimate of the soil following the invasion of the stands by rainforest understoreys. Measurements made during a period of 2 years showed that healthy stands had mean annual soil temperatures greater than 7°C; beneath unhealthy stands the mean annual soil temperatures were less than 7°C. The soil beneath affected stands was moister in summer than that beneath unaffected stands; this possibly was the result of fog stripping by the microphyllous rainforest understorey.

When compared with those of healthy stands, the maximum summer soil temperatures at a depth of 4 inches beneath dead and dying stands were depressed by as much as 8°C, and mean annual temperatures were depressed by about 2°C. Mortality is attributed to the inability of established trees to adapt their root: Crown ratios to accommodate changes of this magnitude.

A simple model of eucalypt dieback is proposed to account for both rural and forest dieback, including an increasing range of 'susceptible' species and sites. It associates eucalypt dieback with increased soil moisture and nitrogen status that stresses the roots of established eucalypt trees. These changes affect the physiology of the trees and encourage high rates of folivory and/or fungal pathogenicity".

Jurskis and Turner (2002) developed a simple model of eucalypt dieback (as explained separately in Section 3.2 this is actually eucalypt decline) to account for both rural and forest dieback/ decline. More detail on this is provided in Section 6.

Jurskis and Turner (2002) observe:

Repeated defoliation by insects has usually been identified as a major factor in rural and forest diebacks, while mesic understorey development is often an important feature of forest diebacks. Different mechanisms of initiation and reinforcement have been proposed to account for many different forms of dieback. High rates of folivory leading to both rural and forest diebacks, have been related either to high resource availability and tree vigour or to low resource availability and tree stress.

5.4 Fire, forest decline, structure decline, mesophication and changes in soil temperature, dampness and light in other countries of the world

Nowacki et al. (2008) provide an example from the US:

A diverse array of fire-adapted plant communities once covered the eastern United States. European settlement greatly altered fire regimes, often increasing fire occurrence (e.g., in northern hardwoods) or substantially decreasing it (e.g., in tallgrass prairies). Notwithstanding these changes, fire suppression policies, beginning around the 1920s, greatly reduced fire throughout the East, with profound ecological consequences. Fire-maintained open lands converted to closed-canopy forests. As a result of shading, shade-tolerant, fire-sensitive plants began to replace heliophytic (sun-loving), fire-tolerant plants. A positive feedback cycle—which we term "mesophication"—ensued, whereby microenvironmental conditions (cool, damp, and shaded conditions; less flammable fuel beds) continually improve for shade-tolerant mesophytic species and deteriorate for shade-intolerant, fire-adapted species. Plant communities are undergoing rapid compositional and structural changes, some with no ecological antecedent. Stand-level species richness is declining, and will decline further, as numerous fire-adapted plants are replaced by a limited set of shade-tolerant, fire-sensitive species. As this process continues, the effort and cost required to restore fire-adapted ecosystems escalate rapidly.

5.5 Eucalypt crown decline progression following soil changes and growth decline over time

Turner and Lambert (2005) raise an important point for the time it takes for crown decline to occur:

At the times that dieback symptoms are apparent on trees, the processes in the soil have been at a stage that may be termed 'negative' for at least ten years, if not longer. Hence, there is a significant lag between a change in soil conditions and dieback becoming obvious in the tree crowns.

Jurskis (2004 a) list common denominators of decline:

- *Feeder roots and mycorrhizae degenerate before the onset of above-ground symptoms*

- *Dry forests are changing structurally and florlistically*

Jurskis (2008) describes the process:

Tree decline is an insidious process, beginning in the roots of trees before their crowns deteriorate and before other biotic responses and contributing factors become visible..

Barber et al. (2007) notes a case where crown health improved after low intensity fire:

………..preliminary work has indicated that in the year after a fire, crown vigour increased for trees lightly scorched by fire (< 10% of the canopy) compared to trees in an adjacent unburnt area.

Neycken et al. (2022) in a study on European beech highlight declining beech trees which showed predisposing signs for crown dieback by having lower growth rates over a very long period:

Highlights

- *Use of generalized additive mixed models to test growth differences.*
- *Declining beech trees grew slower for more than 50 years compared to vital ones.*
- *Competition and species diversity not relevant for predisposition to crown dieback.*
- *Early-warning signals and resilience indices cannot predict crown dieback.*

and:

European beech (Fagus sylvatica L.) has strongly suffered from the exceptional 2018 drought and subsequent dry years that hit Central Europe. While many trees showed severe signs of crown dieback or died following the 2018 extreme drought, other co-occurring and neighboring trees showed no sign of dieback or only minor damage. The reasons why some trees were more severely impacted than others and which predisposing factors make some trees more vulnerable than others are still poorly understood. Here, we analyzed differences in long-term growth trends, neighborhood composition (competition and species diversity), early-warning signals, and growth responses to past severe droughts of co-occurring vital and severely declining beech trees at six sites in Switzerland. We aimed to connect tree vitality after 2018 with past long-term growth trajectories and investigated whether declining trees had already been more susceptible to drought than vital trees before dieback occurred.

Overall, trees that showed severe crown dieback had a stronger growth decline than vital trees in the last 50 years. Declining trees exhibited stagnating and then decreasing growth trajectories even before signs of crown dieback occurred. Interestingly, we did not find significant differences in growth response to past severe droughts between the vitality classes, with the exception that vital trees recovered faster from past more severe droughts. Further, we could neither detect any difference in the effect of competition and neighborhood species composition on growth response, nor predict crown dieback based on early-warning signals which try to predict regime shifts by sudden changes in the autoregressive coefficient with lag 1, standard deviation and skewness. Our results indicate that unlike vital trees, declining beech trees showed predisposing signs for crown dieback by having lower growth rates during the last 50 years.

6 Model processes of changed land management, eucalypt decline and dieback

Jurskis and Turner (2002) outline a model in relation to changed land management, site changes (including increased organic matter and nitrogen), primary biotic responses and secondary changes:

A simple model of eucalypt dieback is proposed to account for both rural and forest dieback, including an increasing range of 'susceptible' species and sites. It associates eucalypt dieback with increased soil moisture and nitrogen status that stresses the roots of established eucalypt trees. These changes affect the physiology of the trees and encourage high rates of folivory and/or fungal pathogenicity. This model can encompass dieback from dryland salinity, 'high-altitude' dieback in Tasmania, 'bellbird' dieback, 'koala' dieback in Victoria and South Australia, phasmatid outbreaks in New South Wales and Victoria, and potentially extends to 'regrowth' dieback in Tasmania. Reduced application of low- intensity fire is a common agent of changed soil conditions. Additional factors that may apply are fertilisation and modifications to runoff and soil drainage.

Jurskis and Turner (2002) highlight the processes involved below in Figure 5:

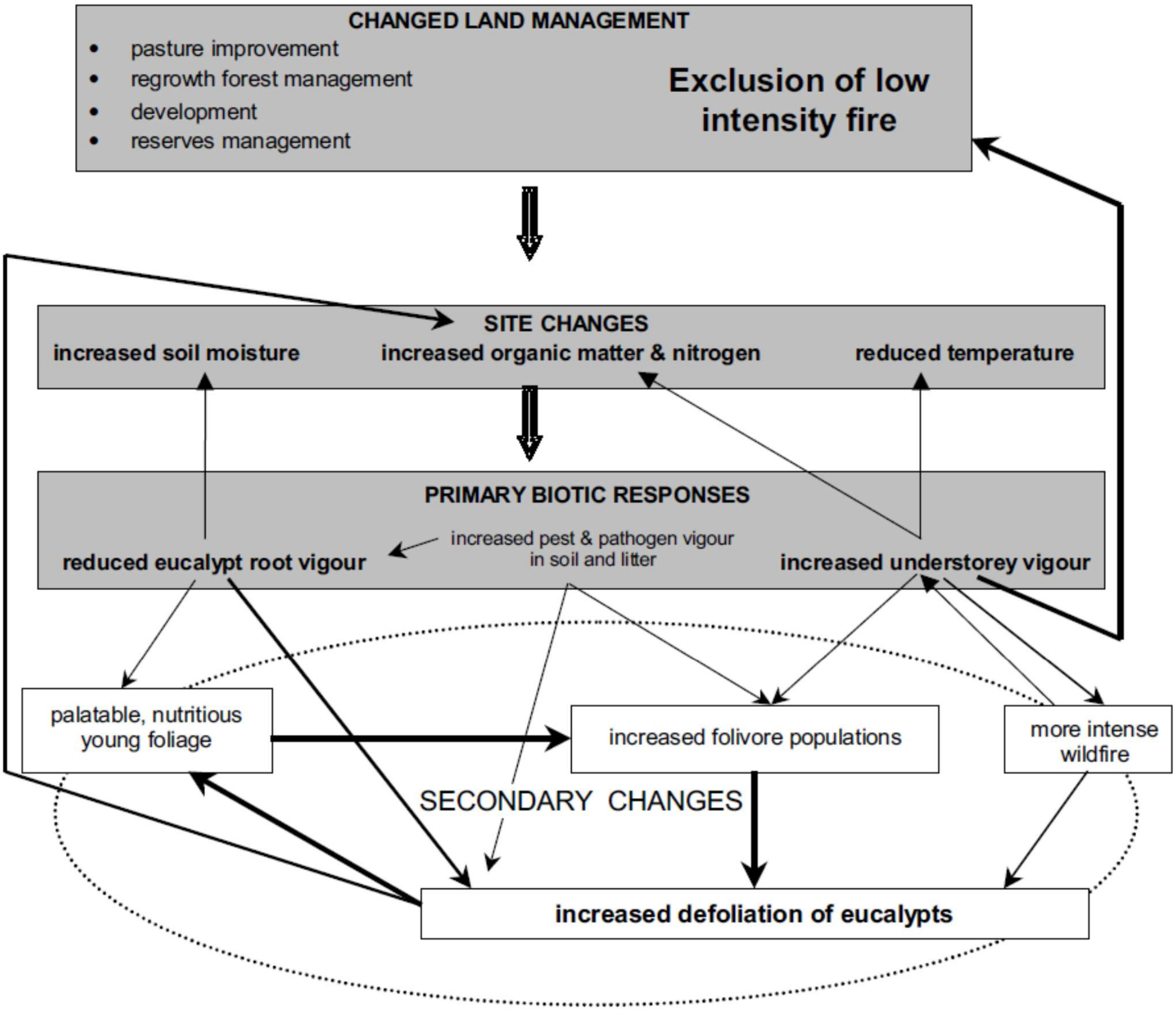


Figure 3. A simple model of eucalypt dieback

Figure 5. A simple model of eucalypt dieback. Detail from the Figure (3) that was extracted from Jurskis and Turner (2002).

It is important to note that Jurskis and Turner (2002) defines dieback that includes decline of large areas of trees: "*Dieback in this discussion refers to the deterioration and death of stands of trees or large areas of trees rather than individual trees. This is sometimes termed tree decline ….".* In addition, Jurskis (2008) clearly sums up the difference between eucalypt decline and dieback.

Jurskis (2004 c) further outline the process in relation to changed fire and grazing regimes below:

With John Turner's help I've extended the simple concept that Landsberg established in rural dieback and Ellis established for high altitude dieback. It can explain a wide range of situations.

1 *human interference changes the environment, soils become richer, damper, and more moderate in microclimate.*

2 *tree roots and mycorrhizae are weakened, while their pathogens and competitors become stronger.*

3 *the changes in tree physiology improve the nutritional value of their leaves and sap resulting in increased pest and disease loads. The increasing shrubbery reinforces microclimatic changes and creates fire management problems*

4 *there are many feedback mechanisms that reinforce the environmental and physiological changes so that the trees get sicker and sicker as the understorey gets thicker and thicker. Intense wildfires accelerate these processes.*

Other eucalypt decline models are outlined in the annexure model processes of eucalypt decline and dieback (Annexure 2).

7 Other references in regards to low intensity fire and grazing and eucalypt decline in Australia

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8 Australian eucalypt decline case studies in relation to lack of low intensity fire and grazing

A series of Australian eucalypt decline case studies in relation to fire and grazing are highlighted below:

8.1 Case studies in NSW

A series of case studies is provided below:

Case study 1.

Jurskis (2008) notes:

At the height of droughts, there were obvious contrasts in the landscape. High, exposed stands experiencing drought scorch had quite full and even canopies of dead brown leaves. Tree trunks, branches and shrubby understoreys were generally not visible from a distance. Lower, sheltered, declining stands had very sparse canopies of epicormic leaves. Tree trunks, branches and shrub understoreys were easily visible from long distances. After rains, drought scorched stands quickly produced epicormic foliage and developed quite full and even canopies of green leaves whereas declining stands developed moderately sparse canopies of leaves that were often discoloured as a result of attack by pests. Tree trunks and branches, and understoreys remained highly visible (e.g. Figure 1).

Figure 6. After drought-break: healthy canopies on ridges, declining canopies in sheltered hollows. (Extracted Figure 1. After drought-break: healthy canopies on ridges, declining canopies in sheltered hollows).

Case study 2 in NE NSW.

A very good case study is provided by Jurskis (2008):

Figure 7. Fence line contrast: grazed/burnt on left, 'protected' on right). Further detail is provided in Jurskis (2008). (**Extracted Figure 3. Fence line contrast: grazed/burnt on left, 'protected' on right).**

The photo highlights the different in management across a fence line is the primary cause of decline.

Other case studies

Other case studies are highlighted in:

- Jurskis (2011 a):
- South East Timber Association website (2023).

8.2 Eucalypt decline case studies across Australia

Jurskis (2004 b) highlights many case studies across Australia outlined in this report titled the “J. W. Gottstein Memorial Trust Fund 2004 Gottstein Fellowship Report”. Observations and studies are very elucidating.

A number of other case studies across Australia are outlined in Jurskis (2004 c).

In addition, Jurskis (2006) highlights additional case studies across Australia in the report titled “Eucalypt decline, forest management and fire management in a range of native ecosystems. Maxwell Ralph Jacobs Fund 2006 Report “Forests NSW. Observations are also very elucidating.

Additional case studies across Australia are outlined in Jurskis and Black (2019).

9 Consequences of lack of low intensity fire and eucalypt decline

Many of the consequences of eucalypt decline are outlined in Sections 3-5.

One paper summarises this issue very well, this being by Jurskis (2011 a) in studies at Eden:

On granitic soils in the Eden region, samples were collected from 156 sites with varying time since fire ranging from one to 39 years. soil analyses showed that after about 10 years without fire, there was substantial accumulation of soil nitrogen (N) (……) and a corresponding decline in the carbon to nitrogen (C/N) ratio and ph. There was a greater accumulation of nitrogen at depth (40 cm) than at the soil surface (0-10 cm) and a greater accumulation in soils with a higher phosphorous (P) concentration at the surface.

Jurskis (2004 c) outlines the consequences with exclusion of fire:

- makes soils cool moist and N-rich
- makes eucalypt leaves young, moist and N-rich
- promotes mycorrhizal dysfunction
- promotes root ‘pathogens’
- promotes ‘arbivory’

Another consequence of forest decline in the absence of fire is highlighted by Close et al. (2011) in relation to structure and understorey:

In Australia, studies indicate that in the long absence of fire: 1) a limited range of shade tolerant woody understorey/midstorey species thrive; 2) dominant overstorey eucalypts prematurely decline and; 3) there is a lack of recruitment of the shade intolerant overstorey eucalypts.

Turner and Lambert (2005) also highlight changes in stand structure relating to lack of regular burning:

Essentially, lack of regular low-intensity burning can lead to reduced stand health and growth, and, in the longer term, changes in stand structure.

Another consequence of forest decline is highlighted by Hurteau and Brooks (2011) in regards to fuel loads, understorey density and structure, no different to Australia:

Forests sequester carbon from the atmosphere, and in so doing can mitigate the effects of climate change. Fire is a natural disturbance process in many forest systems that releases carbon back to the atmosphere. In dry temperate forests, fires historically burned with greater frequency and lower severity than they do today. Frequent fires consumed fuels on the forest floor and maintained open stand structures. Fire suppression has resulted in increased understory fuel loads and tree density; a change in structure that has caused a shift from low- to high-severity fires. More severe fires, resulting in greater tree mortality, have caused a decrease in forest carbon stability. Fire management actions can mitigate the risk of high-severity fires, but these actions often require a trade-off between maximizing carbon stocks and carbon stability. We discuss the effects of fire on forest carbon stocks and recommend that managing forests on the basis of their specific ecologies should be the foremost goal, with carbon sequestration being an ancillary benefit.

The broad consequences of forest decline is highlighted by Jurskis (2004 a) where broadscale changes to fuels, vegetation and microclimate with reduced burning, have made it increasingly difficult or, in some situations, impossible to reintroduce low intensity fire into forests.

More intense bushfires inevitably occur, creating massive havoc across impact areas, as evidenced in 2019/ 20 and many bushfires before and since.

Nowacki et al. (2008) note the loss of a diverse array of fire-adapted plant communities once covered the eastern United States with these fire-maintained open lands converted to closed-canopy forests and mesophication.

Another consequence of eucalypt decline is highlighted Moore et al. (2016) where healthier trees in SW WA were generally associated with higher reproductive effort, including flowering and fruiting:

Many of the worlds' forests and woodlands are currently showing symptoms of declining condition due to a range of factors, including changing climatic conditions, drought and insect herbivory. Altered abiotic and biotic conditions can influence the condition of trees that can, in turn, affect tree reproductive cycles. However, the potential impact of tree decline on reproductive cycles has rarely been examined. This study investigated the influence of canopy condition on the reproductive cycle of Eucalyptus wandoo Blakely in south-Western Australia. Canopy and seed trap monitoring were used to assess bud production, flowering, fruiting and seed fall over 12 months at 24 sites across two locations (Dryandra Woodland and Wandoo Conservation Park). Time since last fire, rainfall, ambient temperatures and the condition of individual trees were recorded. We found that bud production, flowering and fruiting was correlated with tree condition: healthier trees were generally associated with higher reproductive effort. Time since last fire was also strongly related to the reproductive efforts at both locations…..

There are many other consequences of fire exclusion/ lack of low intensity fire, including:

- Tree decline and death.
- Reinforcement of unnatural fire regimes and nutrient cycling processes.
- Proliferation of many native species that benefit from improved nutrition under unhealthy trees and are often common.
- Proliferation of native or exotic woody plants in dry and moist eucalypt ecosystems shading out many other important native species.
- In many cases a reduction in important flora and fauna habitat, as well as threatened species.
- Loss of habitat for a large number of native fauna due to changes in the crowns, understories and at ground level.
- Loss of biodiversity associated with low intensity fire regimes, including Aboriginal burning regimes.

10 US adaptive management actions to improve forest health, reduce forest decline, and resilience and reduce bushfire risk

There is key US federal legislation in place for work reducing fuel, increasing prescribed burning, improving forest health and expanding community mitigation work under the Bipartisan Infrastructure bill and other legislation. There is a firm commitment to this work through Confronting the Wildfire Crisis – A Strategy for Protecting Communities and Improving Resilience in America's Forests and also the earlier National Cohesive Wildland Fire Management Strategy. There is improved funding to reduce fuel loads, prescribed burning, forest thinning and community protection. Firefighter and public health and safety are critical issues as well as infrastructure and utilities protection and there is active community involvement in fire management and this will increase.

Adaptive approaches used in the US include forest management to improve forest health, resilience and reduce bushfire risk. The USDA has useful references in regards to resilient fire management:

1. USDA Forest Service Fact Sheet Management to Improve Forest Resilience and Reduce Wildfire Risk. It is attached as a link.

   https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/Improving-Forest-Resilience.pdf

2. USDA Forest Service Fact Sheet Treating Hazardous Fuels at a Scale That Makes a Difference is very good. It is attached as a link. _https://www.fs.usda.gov/sites/default/files/fs_media/fs_document/Treating-Hazerdous-Fuels.pdf. The document notes that a combination of thinning and prescribed fire Is best for forest health.
3. Confronting the Wildfire Crisis A Strategy for Protecting Communities and Improving Resilience in America's Forests FS-1187a (https://www.fs.usda.gov/sites/default/files/Confronting-Wildfire-Crisis.pdf) and associated documents in mid-January 2022. The document notes *"This is the new wildfire reality facing much of the West (US): it is nothing less than a forest health crisis. A healthy forest is resilient— capable of self-renewal following drought, wildfire, beetle outbreaks, and other forest stresses and disturbances—much as a healthy person stands a good chance of recovering from a disease or injury".*

Stephens et al. (2018) make a recommendation in regards to the importance of adaptive management in California:

Massive tree mortality has occurred rapidly in frequent-fire-adapted forests of the Sierra Nevada, California. This mortality is a product of acute drought compounded by the long-established removal of a key ecosystem process: frequent, low- to moderate-intensity fire. The recent tree mortality has many implications for the future of these forests and the ecological goods and services they provide to society. Future wildfire hazard following this mortality can be generally characterized by decreased crown fire potential and increased surface fire intensity in the short to intermediate term. The scale of present tree mortality is so large that greater potential for "mass fire" exists in the coming decades, driven the amount and continuity of dry, combustible, large woody material that could produce large, *severe fires. For long-term adaptation to climate change, we highlight the importance of moving beyond triage of dead and dying trees to making "green" (live) forests more resilient.*

Franz HS(2018) highlights a good example of a forest health strategic plan, this being 20-Year Forest Health Strategic Plan for Eastern Washington. The 20-Year Forest Health Strategic Plan provides a framework that can result in accelerated planning and implementation of forest health treatments to improve the ecological functions of forest ecosystems and the economic climate for rural communities and the people of Washington State.

In relation to the 20-Year Forest Health Strategic Plan for Eastern Washington:

Forest health is defined in state statute as "the condition of a forest being sound in ecological function, sustainable, resilient, and resistant to insects, diseases, fire and other disturbance, and having the capacity to meet landowner objectives" (RCW 76.06). In 2004, the Commissioner of Public Lands was designated as the state's lead to improve forest health (RCW 76.06). Concurrently with this designation, the state legislature emphasized the need for coordination across land ownerships—federal, state, private, and tribal—in recognition that forest conditions on one property can pose risks to adjacent properties. Wildfire, insects, disease, and invasive species often spread indiscriminately across land ownership boundaries.

As noted by Commissioner of Public Lands Hilary Franz in regards to the 20-Year Forest Health Strategic Plan:

We have a forest health crisis in our state. And because of our forest health crisis, we are seeing more catastrophic wildfires. Hot, dry conditions coupled with diseased and dying forests are leading to explosive wildfires, which threaten our communities and fill our summer skies with smoke.

In central and eastern Washington alone, we have 2.7 million acres of unhealthy forest. That's why, under the leadership of Commissioner of Public Lands Hilary Franz, more than 33 organizations and agencies came together in 2017 to address the crisis with a 20-Year Forest Health Strategic Plan. This plan, grounded in science, sets a bold goal of restoring 1.25 million acres of forest to healthy conditions, increasing fire resilience and better protecting our communities. This ambitious scale of forest restoration is unprecedented in our state.

As of Oct. 31, 2022, DNR and our partners have completed forest health treatments on nearly 500,000 acres across central and eastern Washington. We launched the Forest Health Treatment Tracker in 2021 to map the planned, completed and in-progress forest health treatments across Washington. The tool is interactive and illustrates the scale at which treatments are taking place across landscapes, land ownerships and ecosystems. The treatment tracker will be updated on a regular basis as new information is reported by landowners and land managers.

By actively managing our forests – using strategies such as prescribed burns and thinning – we can restore forests to a more natural and resilient condition. We can bring our forests back to health, boost jobs in rural Washington, and reduce the threat of wildfires.

11 The importance of adaptive management in relation to low intensity fire and grazing in Australian forests to soundly address eucalypt decline

Jurskis et al. (2003) highlight the importance of refocussing fire management in Australia:

Precautionary fire management should be encouraged by:

- *developing guidelines and prescriptions for landscapes, not individual plants and animals*
- *developing prescriptions to control the extent and spatial variability of fires by controlling fire behaviour, rather than prescribing artificial exclusion zones and fire intervals*
- *recognising that low intensity burning protects edaphic controls and sensitive species, so that perceived conflicts between human and environmental protection are largely unreal*
- *recognising increasingly extensive high intensity fire regimes and eucalypt decline as consequences of fire exclusion that must be considered in planning.*

Turner and Lambert (2005) raise important issues in relation to low intensity fire return cycles:

The baseline or control is a 'normal' low-intensity fire cycle (3–6 y). Absence of burning is the equivalent of a treatment. Stands affected by dieback but in the final stages may be recoverable, but will probably require three or more fire cycles or the effects of continuous grazing to restructure the understorey and have an impact on soil nitrogen pools before any improvement in the health of the overstorey is observed. Modifications to the understorey (such as mechanical disturbance of weeds) under this model will exacerbate the rate of dieback..

Based on rates of N accumulation in the absence of fire and N removal by prescribed burning, Turner et al. (2008) suggested a period of 5 years*: To maintain a stable C/N ratio with low mineral N production, a fire periodicity is required where N losses are about equivalent to N inputs. If inputs of N were about 12 kg N ha1 year1 and losses in low intensity fire were 65 kg N ha1, a period between fires of about 5 years would maintain stability. This would vary according to the fertility of the soil and the fire intensity.*

Jurskis (2004 d) highlight the need to adapt fire and grazing management in Australian forests:
There is sufficient evidence and an urgent need to adapt our management of fire and grazing in forests to deal with the increasing problem of forest decline and wildfires in conservation reserves and multiple use forests. Ecological burning regimes should be designed in the context of the natural pre-European fire regimes and forest structures rather than basing them on theoretical life cycle analyses of particular plants. Ecological burning regimes will assist in protecting social and economic as well as ecological values, because they will prevent structural changes that hamper fire management. In situations where fire has been excluded, but grazing has maintained healthy open forests, any withdrawal of grazing should be accompanied by reintroduction of frequent low intensity fire regimes.

Jurskis (2003) highlight returning low intensity fire to the landscape:

Ecological assessments of prescribed burning should start from a pre-European landscape as the optimum position. That is, a landscape with much open and grassy forest maintained by frequent, low intensity fire. They should recognise that grassy eucalypt forests have been substantially depleted by clearing, and that many remnants are unnaturally shrubby and weed infested, with declining canopies. They should recognise that high intensity fires are more frequent and extensive, and low intensity fires are less prevalent than in the pre- European landscape. Thus many ecosystems and species are threatened by both fire exclusion and frequent high intensity fire. Ecological assessments should recognise that fire exclusion has profound impacts in ecosystems that evolved with frequent fire. Fire management should aim to restore some balance by increasing the proportion of low intensity fire in the landscape to protect both grassy, fire dependent ecosystems and also fire sensitive ecosystems such as rock outcrops and rainforests. Strengthened edaphic control of fire and reduced high intensity fire in the landscape will also protect human life and property.

St Clair and Jurskis (2010) raise important factors in regards to restoration programs:

Restoration programs can be ineffective or even counterproductive if they focus on secondary factors and symptoms of decline or attempt to restore elements of ecosystems rather than restoring healthy ecosystem processes. Some examples of successful and unsuccessful conservation or restoration measures in temperate Australian forests and woodlands are discussed.

Effective restoration can improve forest health and productivity and reduce fire risks by restoring natural resilience, reducing fuels loads and vertical profiles and increasing discontinuity in fuels.

Restoration at a landscape scale will require broad community support involving public and private landholders and various community groups. In Australia, Landcare groups and District Bushfire Management Committees can support and implement restoration programs. The Bushfires Cooperative Research Centre has increased interstate knowledge transfer and capacity building in Australia, however there is scope for improvement nationally and internationally.

Jurskis (2016) raises an important issue in regards to adaptive management:

Fencing stock out of remnants of native vegetation is a major contributor to rural tree decline. There are many examples in woodlands around Canberra, our national capital, including one in a Remnant Vegetation Conservation Area (a former TSR) at Hall where the stand spiralled into chronic decline during the Millennium Drought. Five years after the drought broke, this stand is still declining. Frequent mild fire should be reintroduced to rehabilitate such stands. Unfortunately, it's mostly too late). (Figures provided in this reference).

12 Opportunities for targeted adaptive regular low intensity fire and land management and research studies in relation to eucalypt decline

Opportunities for targeted adaptive regular low intensity fire and land management in relation to eucalypt decline:

- Observe and assess evidence in the landscape of the impacts of changed fire regimes. Contrasts in forest health due to different fire regimes are often visible between the top and bottom sides of roads, on opposite sides of tenure boundaries, between drainage lines and spurs and between reserves and general management zones.
- Avoid focus on secondary factors and symptoms in relation to eucalypt decline and inadequate assessment of low intensity fire. As noted by St Clair and Jurskis (2010): *Restoration programs can be ineffective or even counterproductive if they focus on secondary factors and symptoms of decline or attempt to restore elements of ecosystems rather than restoring healthy ecosystem processes. Some examples of successful and unsuccessful conservation or restoration measures in temperate Australian forests and woodlands are discussed.*
- Document and photograph to highlight eucalypt decline examples and progression, as well as low intensity fires and post bushfires.
- Consider increasingly extensive high intensity fire regimes and eucalypt decline as consequences of fire exclusion.

- Consider setting up experimental fire and eucalypt decline plots in areas planned and approved for prescribed burning or where prescribed burning has occurred. Understand the importance of regular low intensity burning to reduce incidence of eucalypt decline and inevitable increased risk of intense bushfires where low intensity burning isn't undertaken.
- Consider low intensity burning based on a period between fires which would maintain stability and seek approvals for these. This would vary according to the fertility of the soil and the fire intensity. As noted by Turner et al. (2008).
- Consider undertaking effective forest treatment using fire (and other means such as thinning) to reduce eucalypt decline and improve forest health over large areas of forest, including declining forest, putting greater funding into this rather than endless ongoing research. This would require more effective policies in regards to land and fire management.
- Monitor medium and long term impacts of forest decline and high intensity bushfires on eucalypt flowering.
- Incorporate knowledge gained and expertise from the large scale adaptive fire management being undertaken in the US, including Confronting the Wildfire Crisis – A Strategy for Protecting Communities and Improving Resilience in America's Forests and also the earlier National Cohesive Wildland Fire Management Strategy.

Opportunities for targeted adaptive regular low intensity fire research studies in relation to eucalypt decline:

Undertake observation in relation to inadequate low intensity fire and eucalypt decline:

- Observe and assess evidence in the landscape of the impacts of changed fire regimes. Contrasts in forest health due to different fire regimes are often visible between the top and bottom sides of roads, on opposite sides of tenure boundaries, between drainage lines and spurs and between reserves and general management zones.
- Avoid focus on secondary factors and symptoms in relation to decline and inadequate assessment of low intensity fire.

Target new research considerations in relation to inadequate low intensity fire and eucalypt decline:

- Placement of research experiments/ studies and forest sites/ trials in relation to where decline is occurring and getting worse. Jurskis (2004 a) noted that many studies had been set up in dry ridgetops on well drained soils and that these types are not generally susceptible to decline.
- Undertake research and forest sites/ trials that have an effective design and data collection, including all the key soil factors, mycorrhizae/ fungi/ bacteria, foliar nutrients, crown health, growth rate assessment, understorey assessment and other required parameters. In addition, prescribing burning/ cultural burning philosophies should be included in the trial and design as an essential component.
- Ensure that controls in scientific research/ forest sites/ trials include Aboriginal burning practices/ and forests at the time of first contact with the baseline or control being a low-intensity fire cycle (3–6 y) and absence of burning is the equivalent of a treatment**.** Controls need to at least include control sites with a regular burning history. Research show that repeated burning maintains stable low nutrient conditions suitable for eucalypts.
- Assess prescribed burning should start from a pre-European landscape as the optimum position. That is, a landscape with much open and grassy forest maintained by frequent, low intensity fire.
- Consider setting up experimental fire and eucalypt decline plots in areas planned and approved for prescribed burning. Understand the importance of regular low intensity burning to reduce incidence of eucalypt decline and inevitable intense bushfires where low intensity burning isn't undertaken.
- Consider increasingly extensive high intensity fire regimes and eucalypt decline as consequences of fire exclusion.
- Monitor medium- and long-term impacts of forest decline and high intensity bushfires on eucalypt flowering.
- Undertake research that captures intense and low intensity burning history of the research/ forest sites and trials. The same applies for early history at time of first contact.
- Utilise camera images to highlight eucalypt decline, including al low intensity fires and post bushfires.
- Document and photograph to highlight eucalypt decline examples and progression, as well as low intensity fires and post bushfires.
- Avoid focus on ongoing research that restarts at the beginning of research and ignores key research as highlighted in this review.

13 Conclusions

The review has been designed to tease out the key issues in relation to eucalypt decline with key researcher text available to assist readers in understanding important information, issues and key references. This approach allows integration of key information in one place to better assist readers in understanding the key issues and references.

There are a considerable number of research papers and authors who have identified exclusion of low intensity mild fire as the major cause of eucalypt decline across a number of Australian native forests and woodlands outlined in the references used list.

Key research authors in relation to establishing root cause of eucalypt decline relating to soil changes associated with inadequate low intensity fire include Turner, Lambert, Jurskis, Horton, Landsberg and Ellis. Other useful contributions have been made by Ishaq, Jones, Davidson, Close, Dijkstra and Adams. Howitt also identified eucalypt decline as linked to a reduction in burning in his legendary 1890 paper. There are 66 papers identified in the "key references used for this review" list and an additional 39 other references in the Section 7 list.

Jurskis (2016) makes critical observations in relation to chronic decline:
… chronic decline involving a wide range of arbivores has affected a wide range of eucalypts across Australia since European settlement, and is currently rampant in many areas of forest and woodland. Pasture improvement and/or exclusion of fire and grazing are the major causes of chronically declining health of eucalypts.

Turner and Lambert (2005) detail in relation to the cause of eucalypt decline across Australia in relation to lack of fire;
Crown dieback is occurring in extensive areas of eucalypt forest in east coast Australia. While there is variation across sites and species with regard to the rate and intensity of the development of dieback, there are indications of common causative factors. ……..Evidence indicates that nutrients are a primary factor. Nutrient depletion from soils through the process of immobilisation in biomass as a stand grows has been suggested as a cause, but there is no evidence for this hypothesis. There is evidence of long-term accumulation of nitrogen (total and available) in undisturbed stands, and this leads to nutrient and biochemical imbalances in the foliage together with root morphological changes. Biochemical changes include increases and imbalances in amino acids resulting in the foliage being more attractive to folivores, and consequent increased herbivory. The level of insects or other folivores is a symptom of the problem and not a primary cause of dieback. Regular burning maintains reasonably stable levels of nitrogen within the system and these levels are the long-term norm for many eucalypt ecosystems. Essentially, lack of regular low-intensity burning can lead to reduced stand health and growth, and, in the longer term, changes in stand structure.

Lack of low intensity fire, eucalypt decline and the link to soil factors is explored in great depth in Section 4. Key soil factors relating to eucalypt decline include pH, Aluminium, nitrogen, phosphorus availability, N:P ratio, C:N ratio, organic matter, soil wetness, mycorrhizae and other soil microbiota in some cases. Turner and Lambert (2005) identified three stages from the commencement of the stand establishment in relation to nitrogen accumulation and changes in C:N ratios.

Jurskis (2005 a) got to the root of the decline issue *"It appears that chronic abiotic stress causes tree decline when the function of roots is impaired by changes in soils".* As noted in this review, feeder roots and mycorrhizae degenerate before the onset of above-ground symptoms. Horton (2011) and Horton et (2013) undertook important research in relation *to ectomycorrhizal (ECM) fungal communities.* Horton et (2013) note " *altered soil chemistry associated with eucalypt forest decline mediates changes in the ECM fungal community".*

The author considers that exclusion of frequent low intensity mild fire as the primary cause of eucalypt decline in Australian native forests and woodlands and this has been inadequately recognised in many studies, research, papers, articles, reviews, management plans, legislation, policies and reports on land and fire management. This lack of recognition is in itself a major environmental issue and ignores up to 60,000 years of Aboriginal burning practices across the landscape.

There is rapid expansion of eucalypt decline across Australia as noted by Jurskis (2015) in Chapter 12:

Chronic eucalypt decline has expanded greatly across Australia in the new millennium. Increasing restrictions on mild burning have made forests increasingly vulnerable to drought and waterlogging. With the Millennium and Black Summer Droughts, followed by the inevitable flooding rains that brought them to an end, forests on relatively fertile and well drained sites have rapidly succumbed. The flush of soft young growth across broad areas consequent to the Black Summer fires has led to plagues of foliovores, fungi etc. contributing the problem. Our naturally most resilient forest types such as high quality blackbutt and spotted gum on relatively fertile, well drained sites have rapidly deteriorated. Scrub understories have proliferated compounding the problem.

There are extensive negative consequences of lack of fire and resultant eucalypt decline and these consequences have been identified in Section 9. These consequences highlight the need for urgent on the ground action and adaptive management.

A lot of effort has been undertaken in relation to research on forest decline and diebacks, with little adaptive management responses, at least in Australia. There has also been confusion between the different described diebacks. Researching symptoms of decline rather than primary factors has resulted in a lot of lost funding, time and lost opportunities for adaptive management. There has been confusion between dieback and eucalypt decline as noted by Jurskis (2008) *"Confusion arises from a failure to distinguish between dieback and chronic decline of trees.*

Diebacks are associated with natural climatic extremes such as drought, and recovery occurs once conditions ameliorate. Chronic declines are associated with environmental changes caused by human management, and trees continue to decline after climatic conditions improve".

There is often evidence in the landscape of the impacts of changed fire regimes with contrasts in forest health/ decline due to different fire regimes that are often visible. There are opportunities to observe this by assessing opposite sides of tenure boundaries; the top and bottom sides of roads; between drainage lines and spurs and between reserves and general management zones in areas where decline has commenced. The case studies in Section 8 highlight case study examples. Figure 7 fence line contrast: grazed/burnt on left, 'protected' on right) highlights major differences in eucalypt decline on opposite sides of a fenced boundary. There are also a large number of other case studies across Australia referenced in Section 8, including two references prepared by Jurskis, the "J. W. Gottstein Memorial Trust Fund 2004 Gottstein Fellowship Report" and the "Maxwell Ralph Jacobs Fund 2006 Report" Forests NSW. Observations are also very elucidating.

Hessburg et al. (2005) examines the issue of dry forests and wildland fires of the inland Northwest USA and also changed forest structure and notes that dry forests of the present-day no longer appear or function as they once did and landscapes are increasingly homogeneous and the regional landscape is set up for severe, large fire and insect disturbance events.

The key US federal legislation commitment in place reducing fuel loads, increasing prescribed burning, improving forest health and expanding community mitigation work under the Bipartisan Infrastructure bill and other legislation provides a useful adaptive management role model for Australian forests suffering decline or likely to suffer decline. Franz HS(2018) highlights a good example of a forest health strategic plan, this being 20-Year Forest Health Strategic Plan for Eastern Washington

Getting to the root of the decline issue is time critical, inaction in relation to this issue results in continuation of eucalypt decline across Australia and is resulting in increasing areas of eucalypt decline, more open eucalypt crowns and forests with dense understoreys and increased bushfire risks and impacts. As a consequence, this has impacts on flora and fauna species, both in bushfires and also in reduced habitat opportunities before and after bushfires due to the density of understories. Fire management and any further research in relation to eucalypt decline should be targeted at the the primary cause of eucalypt decline in Australian native forests and woodlands i.e. exclusion of frequent low intensity mild fire.

If landholders such as farmers ignored Australian tree soil health and soil condition issues that were involved in pest, disease and plant health declines, they would lose financially, especially over a long period. So what is different to forest soil changes and associated eucalypt decline? Why aren't these issues being adequately considered and managed across Australian forests at all levels of government and key agencies, using sound and realistic forest health policies as being used in the US.

Based on rates of nitrogen accumulation in the absence of fire and nitrogen removal by prescribed burning, Turner et al. (2008) suggest a prescribed burning return period of 5 years. Jurskis (2004 d) highlights the need to adapt forest fire and grazing management to address the increasing problem of forest decline and wildfires in forests, designed around natural pre-European fire regimes and forest structures rather than basing them on theoretical life cycle analyses of particular plants. More targeted low intensity fire management would be a positive step forward. Low intensity fire in SE Australian states is of the order of 1% of forest area per year, an extremely low rate, contributing to the increase in eucalypt decline.

Key references used for this review in regards to fire and eucalypt decline in Australia

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Annexure 1. Ellis et al. 1980 research on Recovery of Eucalyptus delegatensis from high altitude dieback after felling and burning the understorey in Tasmania

Details on the selected blocks:

Eastern Block, Ben Ridge. (Grid Ref: 508201). This Block of 5.1 ha is located on a broad, well drained ridge-top. It was last burned about 1935 and no dieback was recognisable in 1963. This area had been part of a grazing lease and had been burned relatively frequently before 1935 (2023 added note last fire was 28 years before treatment)

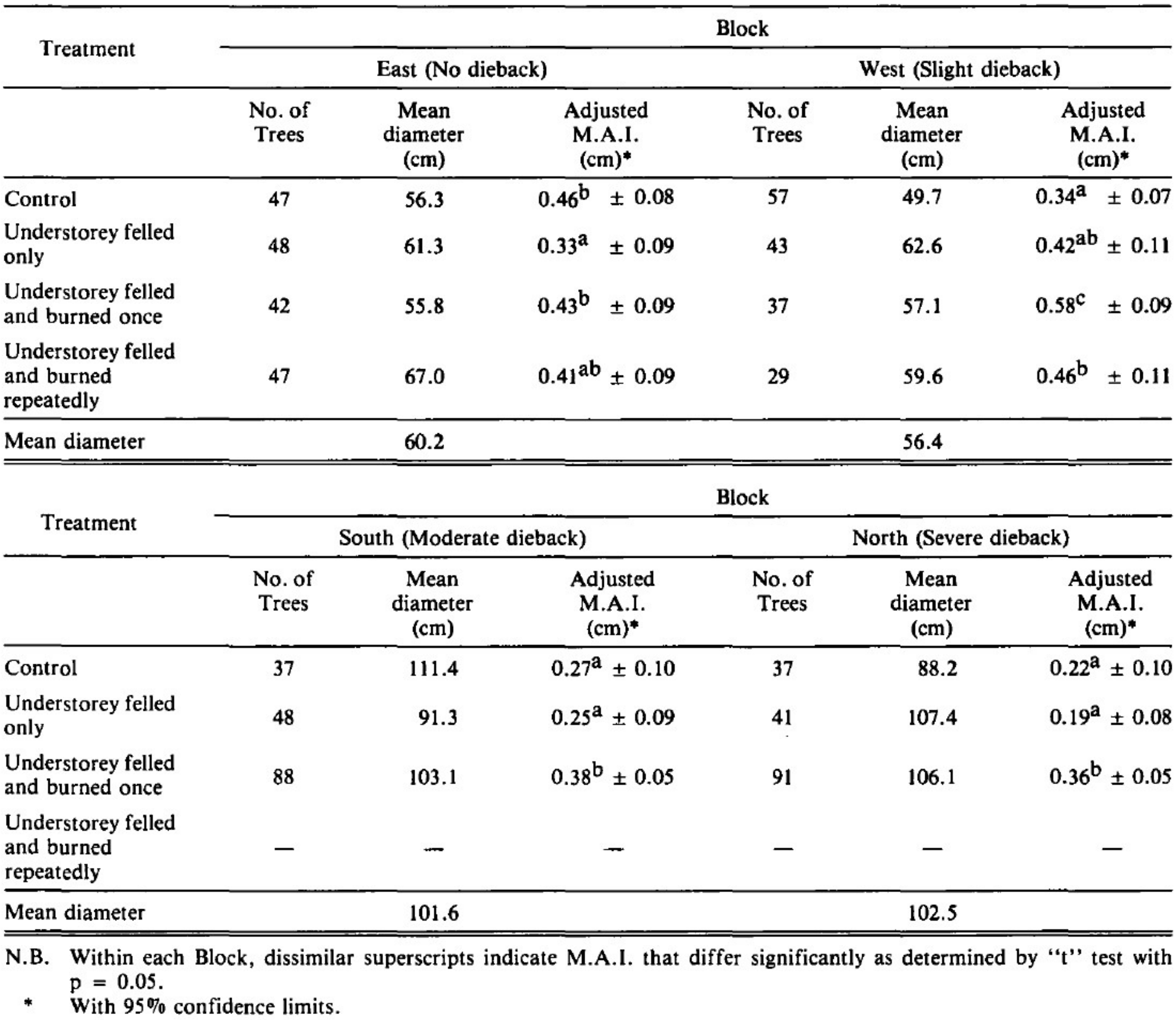
Western Block, Ben Ridge. (Grid Ref: 490202). This Block covers 5 .l ha of another broad, well drained ridge-top. It was last burned about 60 years before establishment of the experiment and the presence of dead and leafless twigs and small branches. (2023 added note last fire was 60 years before treatment)

Southern Block. This block occupies 11.3 ha of a low ridge. It is moderately well drained with wetland on two sides and gentle slopes to creeks on the others. It was last burned about 80 years before establishment. In 1963 moderate dieback of crowns was present in most size classes and several older trees were dead, along with most of the regrowth that had originated from the last fire. (2023 added note last fire was 80 years before treatment)

Northern Block, Paradise Plains. (Grid Ref: S63223). This block of 12.1 ha is on the S. E. aspect of a low rise surrounded by wetland. It is ill-drained, with a high water table and several small streams of low gradient. It was last burned about 80 years before establishment probably by a fire of low intensity. Severe dieback of crowns was present in all size classes and there were many dead trees in 1963. (2023 added note last fire was 80 years before treatment)

Tables extracted from the paper:

Table 1. Comparison of treatments within Blocks. Initial mean diameter and mean annual increment in diameter (M.A.!.) per tree, 1%3/4-1976 Means adjusted from covariance analysis.



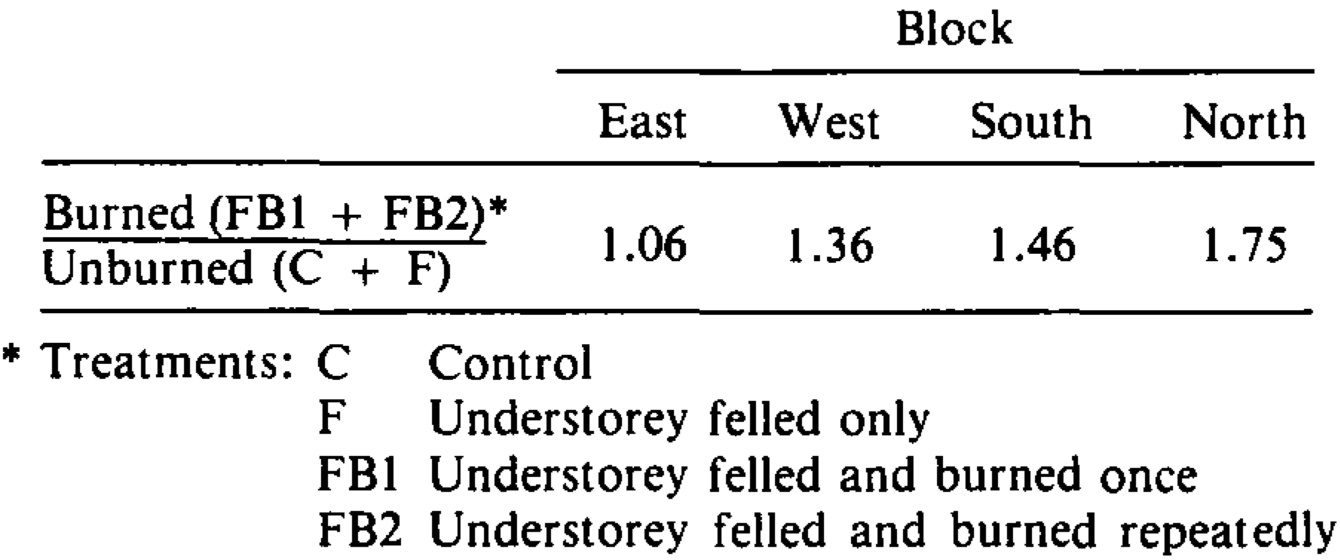
Treatment	Block					
	East (No dieback)			West (Slight dieback)		
	No. of Trees	Mean diameter (cm)	Adjusted M.A.I. (cm)*	No. of Trees	Mean diameter (cm)	Adjusted M.A.I. (cm)*
Control	47	56.3	0.46^{b} ± 0.08	57	49.7	0.34^{a} ± 0.07
Understorey felled only	48	61.3	0.33^{a} ± 0.09	43	62.6	0.42^{ab} ± 0.11
Understorey felled and burned once	42	55.8	0.43^{b} ± 0.09	37	57.1	0.58^{c} ± 0.09
Understorey felled and burned repeatedly	47	67.0	0.41^{ab} ± 0.09	29	59.6	0.46^{b} ± 0.11
Mean diameter		60.2			56.4	

Treatment	Block					
	South (Moderate dieback)			North (Severe dieback)		
	No. of Trees	Mean diameter (cm)	Adjusted M.A.I. (cm)*	No. of Trees	Mean diameter (cm)	Adjusted M.A.I. (cm)*
Control	37	111.4	0.27^{a} ± 0.10	37	88.2	0.22^{a} ± 0.10
Understorey felled only	48	91.3	0.25^{a} ± 0.09	41	107.4	0.19^{a} ± 0.08
Understorey felled and burned once	88	103.1	0.38^{b} ± 0.05	91	106.1	0.36^{b} ± 0.05
Understorey felled and burned repeatedly	—	—	—	—	—	—
Mean diameter		101.6			102.5	

N.B. Within each Block, dissimilar superscripts indicate M.A.I. that differ significantly as determined by "t" test with $p = 0.05$.

* With 95% confidence limits.

Table 2. Stimulation to growth due to burning. Ratio of adjusted mean annual growth in diameter on burned plots to that on unburned plots, 1963/4-1976.



	Block			
	East	West	South	North
$\frac{\text{Burned (FB1 + FB2)*}}{\text{Unburned (C + F)}}$	1.06	1.36	1.46	1.75

* Treatments:
C Control
F Understorey felled only
FB1 Understorey felled and burned once
FB2 Understorey felled and burned repeatedly

Table 3. Relative rates of growth in two periods. Ratio of adjusted mean annual increment in diameter Treatment v control 1963/4-71 and 1971-76.

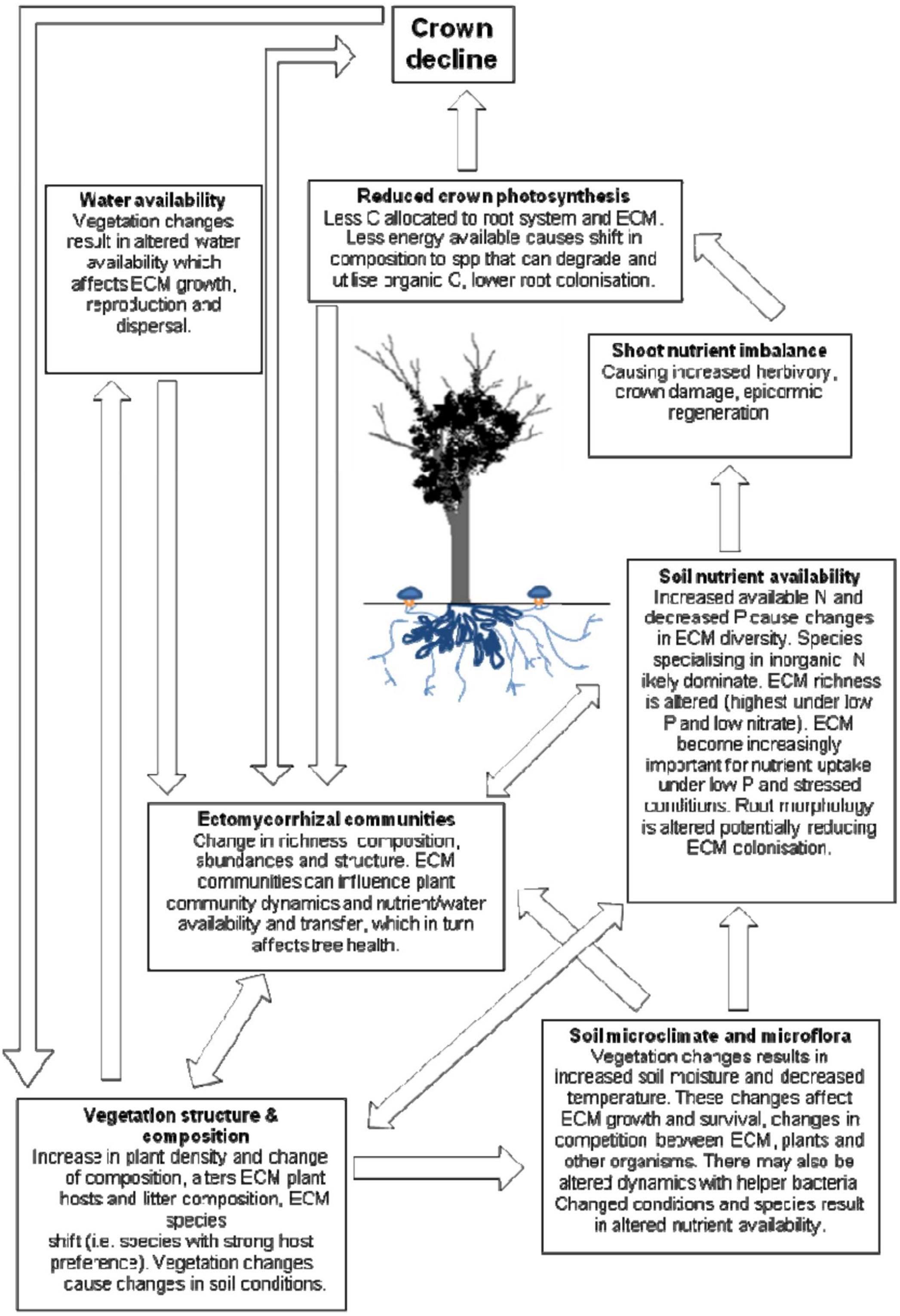
Treatment	Block							
	East		West		South		North	
	1963-71	1971-76	1963-71	1971-76	1964-71	1971-76	1964-71	1971-76
Control	100	100	100	100	100	100	100	100
Understorey felled only	70	66	129	96	109	115	41	134
Understorey felled and burned once	89	85	160	265	191	133	156	176
Understorey felled and burned repeatedly	80	105	117	209	—	—	—	—

Annexure 2 Model processes of eucalypt decline and dieback

Other eucalypt decline models are outlined below:

Horton (2011) proposed a model:

5.0 Ectomycorrhizal and eucalypt decline ecology



Crown decline

Reduced crown photosynthesis
Less C allocated to root system and ECM. Less energy available causes shift in composition to spp that can degrade and utilise organic C, lower root colonisation.

Water availability
Vegetation changes result in altered water availability which affects ECM growth, reproduction and dispersal.

Shoot nutrient imbalance
Causing increased herbivory, crown damage, epicormic regeneration

Soil nutrient availability
Increased available N and decreased P cause changes in ECM diversity. Species specialising in inorganic N likely dominate. ECM richness is altered (highest under low P and low nitrate). ECM become increasingly important for nutrient uptake under low P and stressed conditions. Root morphology is altered potentially reducing ECM colonisation.

Ectomycorrhizal communities
Change in richness composition, abundances and structure. ECM communities can influence plant community dynamics and nutrient/water availability and transfer, which in turn affects tree health.

Vegetation structure & composition
Increase in plant density and change of composition, alters ECM plant hosts and litter composition, ECM species shift (i.e. species with strong host preference). Vegetation changes cause changes in soil conditions.

Soil microclimate and microflora
Vegetation changes results in increased soil moisture and decreased temperature. These changes affect ECM growth and survival, changes in competition between ECM, plants and other organisms. There may also be altered dynamics with helper bacteria Changed conditions and species result in altered nutrient availability.

Figure 1. Detail from the Figure (5.2) that was extracted from Horton (2011).

A conceptual model of the process of eucalypt decline showing how decline affects the ectomycorrhizal community, and feedbacks from the ectomycorrhizal community into the decline process. Changes in both vegetation dynamics in the understorey and overstorey, affect the ECM community through changed host species and densities, competition for nutrients and water, and changed litter. Vegetation changes contribute to a changed soil environment, especially in type and availability of nutrients, in which ECM function, community structure and composition are tightly linked. The ECM community also both responds and contributes to changes in soil nutrients. These changes cause a cascade of changes through the ecosystem, altering ECM communities and ultimately leading to tree decline, which then feeds back to ECM community structure and function.

Close et al. (2009) propose a model of 'premature tree decline' whereby an absence of fire hastens the mortality of overstorey eucalypts in some forests:

Abstract

We propose a model of 'premature tree decline' whereby an absence of fire hastens the mortality of overstorey eucalypts in some forests. This model is relevant to some temperate Australian forests in which fire regimes have shifted from relatively frequent before European settlement to infrequent following settlement. The increased development of midstorey vegetation and litter accumulation has occurred since European settlement in some specific examples of Australian forests and woodlands. Our model proposes that in the long absence of fire: 1. midstorey vegetation reduces the availability of soil water for eucalypts and; 2. Eucalypts have less access to P and/or cations as these elements become locked up in soil, litter and midstorey biomass. We highlight important knowledge gaps and argue that research into ecological burning, for eucalypt health and other values such as biodiversity, is urgently required.

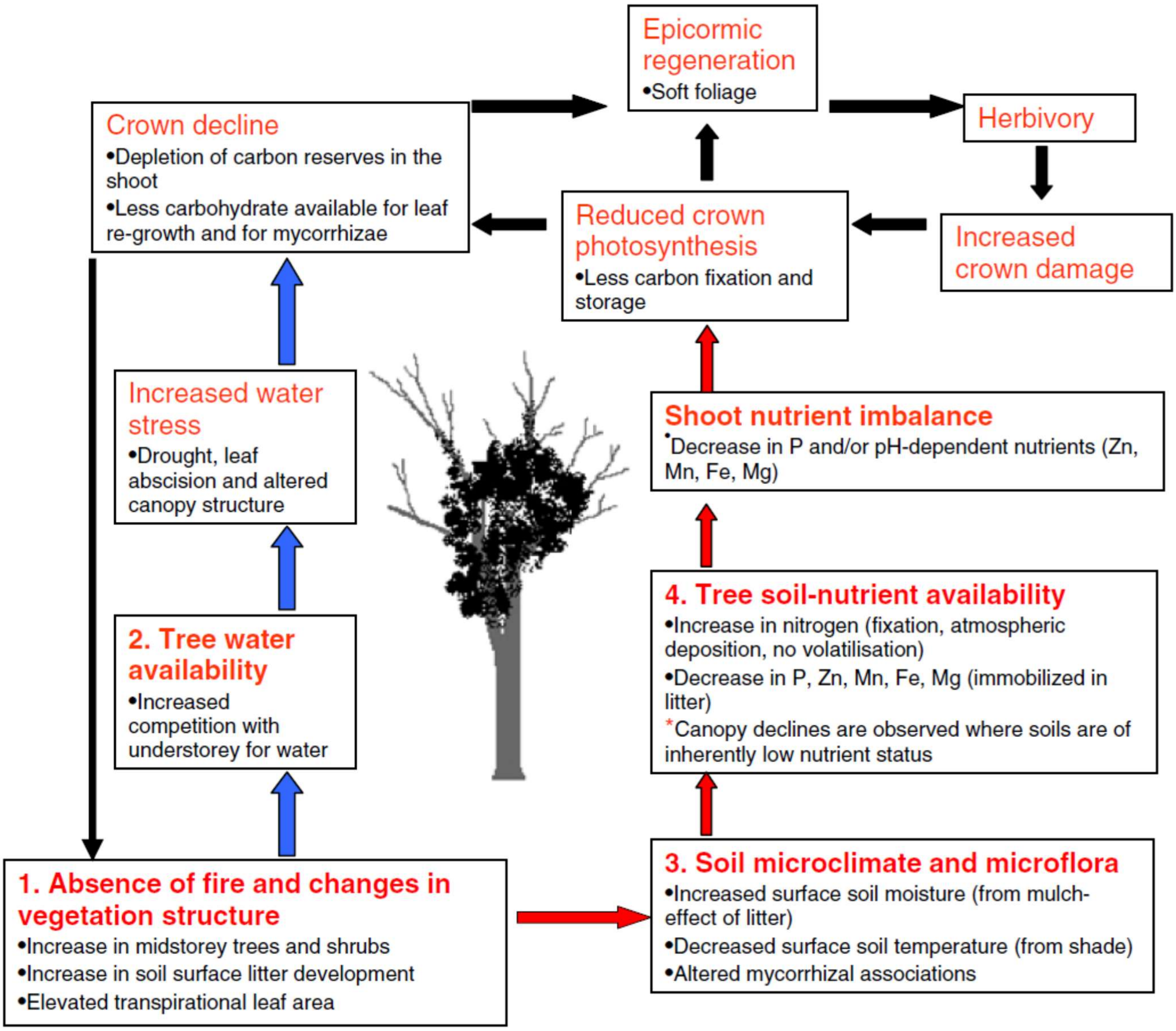


Figure 2. Detail from the Figure (1) that was extracted from Close (2009).

A model of premature decline of temperate overstorey eucalypts in temperate Australian eucalypt forests. 1. A long absence of fire (this timeframe varies between forest types, e.g. ca. 30 years in coastal Eucalyptus gomphocephala in the Mediterranean climate of south west Western Australia to 150 years in cool, wet, high altitude Eucalyptus delegatensis forests of Tasmania) leads to the development of dense midstorey vegetation. 2. The developed midstorey competes for soil available water with the overstorey eucalypts. Competition for soil water, coupled with periodic drought, causes water stress, leaf abscission, altered canopy structure, altered plant carbon balance and increased epicormic shoot development in overstorey eucalypts. 3. The absence of fire leads to a build-up of soil surface litter that moderates soil surface temperatures leading to wetter, cooler soil surface conditions (mesophication;……) that may be less favourable to mycorrhizae of eucalypts that are particularly important for P acquisition. 4. Soil nitrogen accumulates via fixation and atmospheric deposition, and P, Zn, Mn, Fe and Mg become immobilised in soil surface litter (…..). Overstorey eucalypts become deficient in P or soil-pH dependent micronutrients, limiting photosynthesis and causing leaf abscission that leads to further epicormic shoot development. The foliage of epicormic shoots is more susceptible to herbivory (……….) due to decreased lignin and increased digestive value of foliage. Greater occurrence of herbivory further reduces crown leaf area and contributes to decline

Conclusions
The main conclusions drawn from this review underpin our model of premature decline of temperate Australian overstorey eucalypts (Fig. 1). These are: (1) low fire frequencies since European settlement have promoted the development of dense, shade-tolerant midstorey vegetation (ecological drift) and the decline of overstorey eucalypts in particular areas across a wide range of forest types in temperate Australia. Where this occurs, the developed midstorey vegetation (2) competes with overstorey eucalypts for soil water, and (3) alters soil microclimate conditions

that deleteriously affect overstorey eucalypt-ectomycorrhizal interactions. Thus, (4) fire plays a crucial role in controlling tree nutrient-availability by increasing soil pH and the availability of P and cations.

We highlight four clear parallels between the decline of northern American forests and Australian eucalypt forests in response to the long absence of fire: (1) the increased development of midstorey vegetation, the decline of fire tolerant tree species and the dominance of shade tolerant species; (2) increased total stand water use and increased mortality due to drought of fire tolerant/shade intolerant overstorey trees; (3) altered soil microclimate and microbial dynamics and; (4) increased occurrence and risk of wildfire in xeric P. ponderosa systems but decreased occurrence and risk of wildfire in mesic oak systems (mesophication; ……—the latter is clearly similar to the mesophication of wet eucalypt forests, such as temperate E. delegatensis forests (….). The main divergence between ecological processes appears to be the effect of a decrease in fire frequency on plant-availability of P and cations that occurs in Australian but not in North American forest systems. We speculate that this is due to inherently younger and generally less weathered soils in North American relative to Australian forest systems.

(Refences provided in Close et al. (2009) paper).