A world review of forest decline in relation to inadequate regular mild fire and consequent changes in soils, nutrients, mycorrhizae and other soil factors

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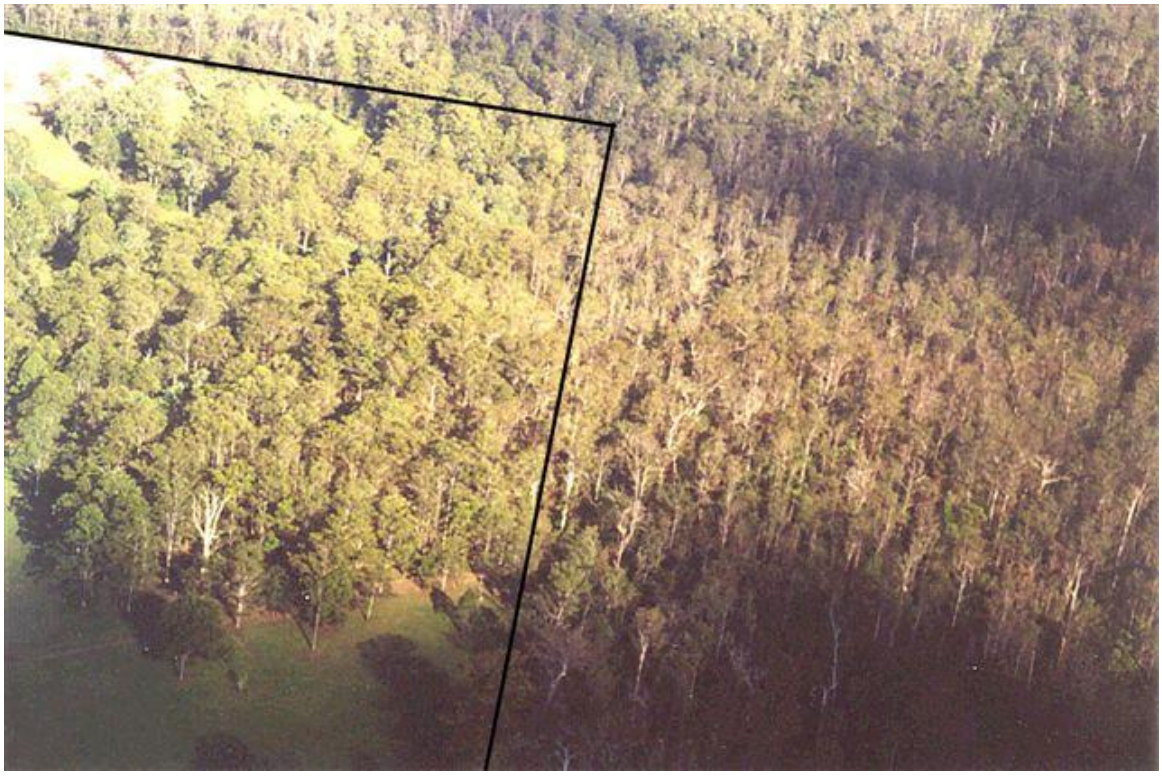
5 January 2025



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1 Introduction

An important factor influencing eucalypt decline across Australia is the extremely low levels of regular mild burning across most Australian states for a considerable period now. The author considers that 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 a number of studies, research, papers, articles, reviews, management plans, legislation, policies and reports on land and fire management.

The author considers that exclusion of frequent low intensity mild fire as a primary cause of forest decline in native forests across the world, and detail is outlined in this review.

The author considers that there has been a focus on symptoms and contributors, not the cause of inadequate regular mild fire which causes cooler damper soils and soil chemical changes, mycorrhizae and roots to deteriorate, and crowns which thin and produce soft young leaves which provide better nutrition for insect and other pests and some fauna species.

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.

There are a considerable number of research papers and authors that identify exclusion of frequent mild fire as a/ the major cause of forest decline across a number of world native forests and woodlands, as outlined in this review. Many of these are outlined in O'Donnell (2023).

This review focusses mainly on the issue of exclusion of frequent low intensity mild fire as a/ the primary cause of forest decline across world's native forests and woodlands and includes discussion around other aspects of active and adaptive management of forest This is based upon evidence outlined in this document, forest observations and research authors in relation to establishing root cause of eucalypt decline relating to soil and mycorrhizal changes associated with inadequate and irregular mild fire across the world.

2 World review of forest decline, fire, fire regime and composition/ structure change, tree health, water and tree physiology changes, soil nutrient and physical changes, and soil fungal and mycorrhizal changes

The author has undertaken a world view of forest decline in relation to in relation to regular mild fire and changes in tree health, soils/ roots/ tree physiology, mycorrhizae and nutrients.

2.1 Forest decline and changed fire regimes across the world, particularly in relation to lack of regular mild fire and changes in forest composition and structure

Forest decline and changed fire regimes across the world, particularly in relation to lack of regular mild fire and changes in forest composition and structure is considered in the subsections below.

Consideration of this issue by individual authors

The author has undertaken a summary assessment of authors who research this subject area below.

Forestry Corporation of NSW (2020) highlight ecosystem impacts with exclusion of low intensity fire:

Gross changes in ecosystem appearance and health have been observed following exclusion of low intensity fire from grassy eucalypt ecosystems. Formerly grassy eucalypt ecosystems, including many endangered ecological communities, are now characterised by thickening understories of native and/or exotic weeds with the overstory eucalypt crowns in significant to terminal decline. Low intensity burning is no longer possible in these stands and high intensity fire cannot restore the dominance of eucalypts since the seed supply and regenerative capacity of the declining trees has been diminished by repeated defoliation whilst massive regeneration of many weeds would be stimulated. Elevated fuel loads are heavier and there is a greater proportion of green fuels so that more severe weather conditions are required before fires can be ignited and sustained. However, once ignited, flames are higher, fires are more intense, and control is difficult or impossible. As a result, wildfires become more intense, less patchy and larger.

Jurskis (2016) highlights that pasture improvement and/or exclusion of fire and grazing are the major causes of chronically declining health of eucalypts. This is crisp and clear.

Jurskis (2004 a) explains that altered fire and grazing regimes create richer soils and denser understorey, weakening trees and increasing pests, with feedback loops that worsen decline and intensify wildfire risks

Jurskis (2015) summarises detail highlighting that the explorer Howitt (1890) recognised chronic decline of red gum defoliated by insects in East Gippsland as a consequence of not burning and 25 years ago Bob Ellis working in forests, and Jill Landsberg working in woodland pastures, identify connections between soil changes, tree physiology and chronic decline.

Jurskis (2015) traces eucalypt decline in dry and moist forests to reduced mild burning, fertiliser use, and expanded conservation reserves, showing how soil changes and altered nutrient cycles weaken tree resilience and increase decline. He notes that a variety of pests, pathogens and parasites are contributing to the decline and all ages are affected except for young regrowth stands less than about 30 years old.

Jurskis (2004 b) 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.

They key point that human management overrides other factors, such as climatic stress and the presence of pests or pathogens, in initiating decline is a very important point.

Jurskis (2020a) highlights changes in the nutrient cycle, including nitrogen accumulation from reduced burning as a global driver of species compositional shifts in a wide range of world ecosystems and chronic tree decline, with fire helping rebalance nutrient cycles.

Jurskis (2003) observes that reduced low-intensity fire leads to the development of dense shrub layers, declining forest health, and greater wildfire control difficulties in SE Australia.

Jurskis (2005 a) outlines:

Changes in fire regimes have upset the ecological balance in many eucalypt ecosystems (Attiwill 1994), and caused the health and predominance of eucalypts to decline (Jurskis 2005). Increasing populations of other species including mistletoes, shrubs, birds, possums and koalas have been seen by some ecologists as a sign of healthy ecosystems (e.g. Henderson and Keith 2002; Watson 2002; Keith 2004; Shaw et al. 2004; Kavanagh and Stanton 2005), and by others as a sign of ecological imbalance (e.g. Martin 1985; Neyland 1996; Jurskis 2002, 2005; Jurskis et al. 2003).

Jurskis (2005 a) argues that altered fire regimes disrupt ecological balance, causing eucalypt decline and proliferation of mistletoes, shrubs, and arbivores, seen by some as imbalance rather than ecosystem health.

Jurskis and Underwood (2013) review human fires and wildfires on Sydney sandstones and forest structural changes:

We present a case study of ecosystems on the Sydney sandstones to demonstrate that a regime of infrequent high intensity wildfires since European settlement has caused structural changes and reduced spatial diversity. This has put many fire dependent plants at a competitive disadvantage and increased their susceptibility to disease.

Jurskis and Underwood (2013) show that infrequent high-intensity wildfires since European settlement reduced diversity and disadvantaged fire-dependent plants, increasing disease susceptibility.

Jurskis (2011 b) outlines Eucalypt ecosystem information for forests predisposed to chronic decline in NSW:

Abstract
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.

Jurskis (2011c) stresses that frequent low-intensity fire is essential for nutrient cycling and balance; its absence leads to chronic decline, competition, and arbivory.

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.

Jurskis et al (2005) propose that high populations of parasites including mistletoes, native cherries (Santalaceae) and dodder-laurel vines (Cassytha spp.), like high populations of folivorous animals or fungal pathogens, are symptoms of declining health of forests caused by unnatural fire regimes. They note that exclusion of fire may change the soil environment around the roots of trees and affect their physiology, improving the nutritional value of their roots, sap and leaves for pests and parasites.

They observe over about 15 years, populations of mistletoes increased very noticeably in a large, undisturbed Flora Reserve on the Wallagaraugh River near Eden, along with a general deterioration in the health of the trees (Jurskis 2004). Managers have largely excluded fire from this area since it was reserved as State forest about 30 years ago.

The rate of increase in mistletoes was lowest in the frequent burning treatment, despite the fact that the highest density of mistletoes occurred in this treatment in two plots that sampled an extensive stand of yertchuk on a lower slope near a creek.

Jurskis et al. (2005) link parasite outbreaks to fire exclusion and soil eutrophication, showing how altered conditions favour mistletoes, cherries, and pathogens in declining forests. A very useful discussion centred around the higher water potential and higher levels of nutrients and water in unhealthy trees might favour the survival and recruitment of mistletoes.

Williams et al. (2022) note that open eucalypt forests with a grassy understorey are becoming rare in the volcanic landscapes on the Queensland–New South Wales border, as woody plants thicken with the cessation of regular planned burning and the canopy of rarely burnt forest show more signs of dieback. They also note the pattern of healthier eucalypt forest with frequent burning was observed at other South East Queensland sites, Mt Gillies and Spicer's Gap and suggest that long-term frequent burning under mild conditions with good soil moisture maintains grassy eucalypt forest that is resilient to occasional intense wildfires during drought, such as seen in late 2019.

Burrows et al. (2025) find that exclusion of mild fire in karri forests in SW Western Australia worsens canopy decline, with litter depth influencing rhizosphere conditions more than soil chemistry.

Burrows *et al.* (2025) also note.

In fire-prone forests, fire regimes can be harmful or beneficial to tree health. A regime of intense bushfires can cause widespread death and injury to trees, and fire exclusion can alter the structure and composition of forests (e.g. Harvest et al. 2008; Stanton et al. 2014; McCaw and Middleton 2015; Fairman et al. 2015; Williams et al. 2020; Hagmann et al. 2021). The exclusion of frequent mild fire has caused, or been associated with a decline in health of overstorey trees in a variety of Australian

eucalypt forests (Jurskis and Turner 2002; Jurskis 2005; Harvest et al. 2008; Jurskis 2017; Lewis 2020; Williams et al. 2022).

Stanton et al. (2014) show that without regular fire in Queensland, grassy ground cover collapses, leading to rainforest encroachment and structural shifts in open forests and highlight that grasses disappear when the shade of a developing understory reaches a critical level and this can be reached in a period as short as 10 years without fire.

Lee (2021) notes:
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.

Other information in relation to Dr Fletchers studies is highlighted in the link and information below:

- *https://melbourne.sciencegallery.com/sediment-cores-mobile#:~:text=Through%20analysing%20this%20material%20Dr,application%20of%20cultural%20burning%20regimes.*

Across Australia, the sites studied to date by the team show that they only experienced minor fires as they were kept open by Aboriginal land care for Country and management but now ecosystems are characterised by major and/or catastrophic fires and much denser shrub and forests

Research in the Bega Swamp in south east NSW by Paleoecologist Professor Simon Haberle from the Australian National University has provided an analysis of cores from the swamp. He found the sediment, sampled at a very fine resolution, paints a picture of the landscape in freeze frames of every 20 years, stretching back over 15,000 years. “The results show that the number of samples including charcoal has increased since European settlement, confirming other studies that big fires have occurred more frequently than during the time of Aboriginal land tenure in the Australian high country,” Professor Haberle said. “It also shows that in the past mega fires only occurred very rarely, once every 4000 years, and that the current situation of big and intense fires is unusual in the long-term history of the region.” “You see big changes in fire management, because you can look at the charcoal and see what burning regime took place,” he said. “It was a regular regime, Aboriginal people knew how to keep fuel loads lower.”

As Morgan et al. (2020) outline, the current fire management will not sustain the full range of ecosystem processes and biodiversity, nor reduce to an acceptable level the impact of wildfires on human lives and property.

O’Donnell (2025) outlines the importance of regular low forest intensity fire in reducing forest decline in Australia and across the world.

Barber et al. (2007) observe improved crown vigour in trees lightly scorched by low-intensity fire (< 10% of the canopy) compared to unburnt areas.

Nowacki et al. (2008) describe “mesophication,” where fire suppression policies beginning around the 1920’s greatly reduced fire in the eastern US converted open fire-adapted lands into closed canopy forests. This resulted in microenvironmental conditions (cool, damp, and shaded conditions; less flammable fuel beds) continually improved for shade-tolerant mesophytic species and deteriorate for shade-intolerant, fire-adapted species.

Hessburg et al. (2005) highlight that dry forests of the inland Northwest USA have become homogeneous and unsustainable due to fire suppression, increasing vulnerability to severe large fires and insect outbreaks.

Hagmann et al. (2021) document widespread fire deficits in inland Northwest American forests, showing exclusion has increased live and dead vegetation fuel loads, reduced heterogeneity, and heightened vulnerability under climate change,

Section summary

Research across Australia and globally shows that exclusion or lack of regular mild fire has profoundly altered forest ecosystems, driving chronic decline in eucalypts and other fire-adapted species. Authors such as Jurskis, Burrows, and Forestry Corporation of NSW highlight that reduced low-intensity burning leads to soil nutrient imbalances (particularly nitrogen accumulation), dense understories, weakened tree physiology, and heightened susceptibility to pests, parasites, and arbivory. These changes increase fuel loads, making forests more vulnerable to severe, less controllable wildfires.

Evidence from long-term experiments and case studies demonstrates that human management decisions, including fire suppression, grazing exclusion, fertiliser use, and conservation policies, are the primary drivers of forest decline. Indigenous burning practices historically maintained open, resilient forests in many locations, but their disruption by European settlement caused rapid woody thickening, loss of grassy ground layers, and unprecedented megafires.

Other studies from Australia, the USA, and elsewhere reinforce these findings. Williams et al. (2022), Stanton et al. (2014), Fletcher, and Haberle document how fire exclusion collapses grassy ecosystems, promotes vegetation encroachment, and shifts open forests into closed systems within decades. Burrows et al. (2025) show canopy decline in fire-prone forests without mild fire, while Barber et al. (2007) observes improved crown vigour in trees lightly scorched by low-intensity burns. In North America, Hessburg et al. (2005), Hagmann et al. (2021), and Nowacki et al. (2008) describe “fire deficits” and “mesophication,” where suppression policies created homogeneous, fuel-rich forests vulnerable to severe fires and insect outbreaks. Collectively, this research underscores that frequent, low-intensity fire is essential for sustaining nutrient cycles, structural diversity, and long-term forest health, and that its absence has led to widespread decline and heightened ecological imbalance.

2.2 Forest decline and tree health changes in relation to lack of regular mild fire across the world

This section explores forest decline and tree health changes in relation to lack of regular mild fire across the world.

Consideration of this issue by individual authors

Jurskis (2011c) shows that frequent low-intensity fire is essential to maintain natural nutrient cycles and preventing chronic decline in most eucalypt ecosystems. Absence of frequent fire alters these processes, and results soil changes, competition, and arbivory drive ecosystem imbalance and can result in chronic eucalypt decline and gross changes of forest structure, with nearly 18% of NSW forests at risk of eucalypt decline.

Turner et al. (2008) identify that tree health declines in long-unburnt plots are tied to altered soil properties, contrasting with healthier soils in regularly burnt areas.

South East Timber Association (2023) in their valuable document “Use of Fire to Improve Native Forest Ecological Health” outline a number of case studies on the importance of regular low intensity burning maintaining forest health. One case study is provided below:

In the early 1980's, this area was Beaury State Forest. It was grazed and burnt, open and grassy. The trees were all healthy and there were some huge old trees that have since died and fallen after the area was permanently protected. This was the core of the biodiversity hotspot that Calaby identified in the sixties. NPWS still advertises that there are 10 different macropods living there. Without evidence to support this assertion, their ongoing existence in the area is highly doubted, because their grassy forage has been choked out by scrub and lantana.

According to NPWS:

White Gum Moist Forest is threatened by forest eucalypt dieback associated with over-abundant Bell Miners and psyllids (Wardell-Johnson et al. 2006, DEC 2007). This complex process is associated with substantial changes in community composition and structure, including the defoliation and

eventual death of canopy eucalypts, increased densities of mid-stratum plant species and decline in diversity of small forest birds.

In fact it's a very simple process that has been observed and documented on site. Forestry Commission botanists resurveyed some plots 10 years after the original surveys in 1992. Ten plots had been classified as a group typified by grassy understories and frequent burning. Unfortunately, it was suggested that these areas of dry forest should remain unburnt for periods of ten to fifteen years or more to promote biodiversity. By 2002, four of the plots had developed dense shrub understories and were then classified in different floristic groups compared to the original survey. Two of these plots were heavily infested by lantana, and the eucalypts in all four shrubby plots were already showing signs of moderate to severe decline.

Burrows et al. (2025) link canopy decline in karri forests in WA to long fire absence, with litter buildup altering soil conditions. They argue mild burning sustains forest health and resilience, aligning Western science with Aboriginal knowledge of "upside-down country" and "sick trees. They also explain the buildup of mulch in long unburnt forests could be altering soil moisture and temperature regimes, and possibly other physical factors of the soil environment, disfavouring soil microorganisms that are beneficial to karri and favouring those that are harmful. Burrows et al. (2025) also found that exclusion of mild fire in karri forests in SW Western Australia worsens canopy decline

Burrows et al. (2025) found that exclusion of mild fire in karri forests in SW Western Australia worsens canopy decline, with litter depth influencing rhizosphere conditions more than soil chemistry.

Moore et al. (2016) demonstrate that healthier Eucalyptus wandoo trees in southwestern Australia exhibited greater reproductive effort, including flowering and fruiting. Their study links canopy condition and time since fire to reproductive cycles, showing that decline reduces reproductive capacity.

This highlights useful information in relation to reduction in tree water stress, maybe a factor in reducing eucalypt decline occurrence.

A useful reference by Pinho et al. (2020) explores this area in relation to oak trees:

Abstract: Forest decline diseases are complex processes driven by biotic and abiotic factors. Although information about host–microbiome–environment interactions in agricultural systems is emerging rapidly, similar studies on tree health are still in their infancy. We used acute oak decline (AOD) as a model system to understand whether the rhizosphere physicochemical properties and microbiome are linked to tree health by studying these two factors in healthy and diseased trees located in three sites in different AOD stages—low, mid and severe. We found significant changes in the rhizosphere properties and microbiome composition across the different AOD sites and between the tree health conditions. Rhizosphere pH correlated with microbiome composition, with the microbial assemblages changing in more acidic soils. At the severe AOD site, the oak trees exhibited the lowest rhizosphere pH and distinct microbiome, regardless of their health condition, whereas, at the low and mid-stage AOD sites, only diseased trees showed lower pH and the microbial composition differed significantly from healthy trees. On these two sites, less extreme soil conditions and a high presence of host-beneficial microbiota were observed in the healthy oak trees. For the first time, this study gathers evidence of associations among tree health conditions, rhizosphere properties and microbiome as well as links aboveground tree decline symptoms to the belowground environment. This provides a baseline of rhizosphere community profiling of UK oak trees and paves the way for these associations to be investigated in other tree species suffering decline disease events.

Discussion
Interestingly, we found bacteria and fungi previously linked to plant diseases and that were more abundant in oak rhizospheres at Richmond (severe-AOD stage). Examples include members of the families Burkholderiaceae and Xanthomonadaceae, which were also isolated from tissues of oaks affected with AOD [13]; representatives of the families Sphingobacteriaceae and Burkholderiaceae, which were reported in plant rhizospheres after pathogen infection [73]; and plant pathogenic fungi such as Gibberella [74,75] and Phaeoacremonium [76]. Moreover, saprophytic fungi were also more abundant at Richmond as well as in the AOD trees. This suggests that declining trees have poor feeder root health and are undergoing partial root degradation or are too weak to fend off saprophytic

attack. Thus, such organisms are able to take advantage of the situation, which is evidenced by the enrichment in bacteria and fungi with a saprophytic lifestyle and is a consequence of probable high decay material availability. Indeed, the results are supported by previous studies also reporting soil microbiome changes caused by biotic and abiotic forest disturbances, particularly the increase in saprophytic taxa over beneficial species [77,78].

In summary, Pinho et al. (2020) demonstrate that oak decline is linked to rhizosphere pH shifts and microbiome changes. Diseased trees show more pathogenic and saprophytic organisms, while healthy trees retain beneficial microbes, highlighting belowground drivers of forest decline. Their study is very beneficial.

Schoonmaker et al. (2016) show that ageing forests lose growth efficiency despite larger leaf area, due to reduced fine roots and colder soils. This highlights the growing importance of belowground processes in forest vulnerability to stress and mortality risk.

In relation to forest health and opportunities for Australia, O'Donnell (2022) summarises the US Forest Service's wildfire crisis strategy and notes annual US funding for fuels and forest health treatments has been limited and uncertain, and patterns of placing treatments have never approached the scale of the needed work, noting there is a forest health crisis. To restore forest health and reduce wildfire risk, a forest health management includes thinning forests, conducting prescribed fires, and using lightning fires and other "unplanned ignitions" to return fire to the land and restore forest health. O'Donnell notes that in Australia there is generally very poor actioning in regards to forest health and the decline of forest health across Australia's forests, mild fire is an important component of improving forest health and setting up healthy and landscapes.

Section summary

Research across multiple regions demonstrates that the absence of regular low-intensity fire is a major driver of forest decline, balanced ecosystems and forest health. Jurskis (2011) and Turner et al. (2008) highlight that long-unburnt plots suffer soil changes that reduce tree health, while frequent mild fire sustains nutrient cycling and prevents chronic decline, with nearly 18% of NSW forests at risk without it. Case studies from the South East Timber Association (2023) highlight how formerly grazed and burnt forests with healthy trees and diverse fauna shifted to dense shrublands and lantana infestations after fire exclusion, leading to canopy decline and biodiversity loss. Burrows et al. (2025) link karri forest decline in WA to litter buildup from fire absence, which disrupts soil moisture and microbial communities, echoing Aboriginal knowledge of "sick trees." Moore et al. (2016) further show that reproductive effort in Eucalyptus wandoo declines with canopy deterioration tied to fire absence, underscoring fire's role in sustaining resilience and reproduction.

Complementary research emphasises belowground processes as critical drivers of forest health. Pinho et al. (2020) demonstrate that oak decline in the UK is associated with rhizosphere pH shifts and microbiome changes, with diseased trees hosting more pathogenic and saprophytic organisms while healthy trees retain beneficial microbes. Schoonmaker et al. (2016) add that ageing forests lose growth efficiency due to reduced fine roots and colder soils, increasing vulnerability. Together, these findings highlight that forest decline and forest health is shaped by both fire regimes and soil–microbiome interactions. O'Donnell (2022) stresses that prescribed burning, thinning, and managed ignitions are essential for restoring forest health, noting effective fire strategies underway in the US. Overall, the evidence converges on the importance of mild fire and soil processes in maintaining forest resilience, biodiversity, and long-term health.

2.3 Forest decline, fire, soil, soil moisture, root and tree physiology and tree stress across the world

This section explores forest decline, fire, soil, soil moisture, root and tree physiology and tree stress across the world.

Consideration of this issue by individual authors

Underlined sub headings have been used to break up this section.

Fire, mulch buildup and soil moisture changes

Forestry Corporation of NSW (2020) notes that reduced fire in the landscape has led to increased soil moisture and higher susceptibility to soil borne pathogens

Jurskis and Turner (2002) note that the reduced application of low- intensity fire with eucalypts is a common agent of changed soil conditions, including soil moisture and nutrient status.

Burrows et al. (2025) link canopy decline in karri forests in WA to long fire absence, with litter buildup altering soil conditions and also explain the buildup of mulch in long unburnt forests could be altering soil moisture and temperature regimes, and possibly other physical factors of the soil environment, disfavouring soil microorganisms that are beneficial to karri and favouring those that are harmful

Changes in tree physiology and stressors

Castano et al. (2019) emphasise the role of soil microbes, particularly ectomycorrhizal fungi, in alleviating drought stress. Fire-driven soil changes that disrupt these symbioses increase tree vulnerability to water deficits. They note that Ectomycorrhizal (ECM) fungi are also key players in the alleviation of drought stress for trees.

Perry (1982) outlines tree root and crown considerations, describing the root–crown balance, noting fine feeder roots occur in litter and surface soils where fire strongly influences conditions. Root mortality directly affects crown health, making soil changes critical to tree physiology. They also note that approximately 99 percent of the roots occur within the surface meter of soil and extend outward over an area one to two or more times the height of the tree

Bobbink et al. (2010) that their global synthesis shows nitrogen accumulation alters plant physiology, root/shoot ratios, and mycorrhizal infection. These changes reduce resistance to drought, frost, and pathogens, linking soil nutrient imbalances to chronic decline.

Soil drainage and aeration issues and changes

Jurskis (2005 b) distinguishes episodic dieback from chronic decline, attributing the latter to human management such as fire exclusion and pasture improvement. Poorly drained soils exacerbate root impairment, making trees vulnerable to drought and eutrophication.

Jurskis (2020) adds to earlier research work, he shows fire exclusion elevates soil nitrogen, disrupts mycorrhizae, and alters foliar chemistry. These soil-driven physiological changes predispose trees to decline under drought and waterlogging stress.

Drought, waterlogging and flooding

Jurskis (2015):documents rapid expansion of chronic decline across Australia, with fire restrictions increasing vulnerability to drought and waterlogging. Even resilient forest types succumbed as scrub understories proliferated and soil conditions deteriorated.

Jurskis (2008) contrasts drought scorch (episodic, reversible) with chronic decline (persistent, soil-driven). Declining stands in sheltered, poorly drained sites show sparse canopies and pest attack, unlike drought-scorched ridges that recovered after rain.

Jurskis (2008) notes:

ABSTRACT

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 can not 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. This chapter briefly reviews some international literature and uses some case studies from temperate Australia to illustrate the role of drought in diebacks and declines of trees in urban, rural and native forest situations.

Jurskis (2020)
Drought scorch occurred in higher topographic positions and exposed aspects on convex surfaces with shallow or skeletal soils and on some relatively coarse grained deeper soils in lower rainfall areas. Decline mostly occurred in lower topographic positions on more sheltered aspects on concave or flat surfaces and on soils that were not freely draining (Jurskis 2005, 2008).

and:

According to the Researchers, Norton (1886) reported "multiple dieback events" caused by diverse factors such as frost, drought, waterlogging, woodborers or beetles. However, it has become clear that trees lost their resilience to all these stressors consequent to disruption of Aboriginal burning and establishment of improved pastures (e.g. Landsberg et al. 1990; Jurskis 2005, 2015, 2016; Bobbink et al. 2010).

and:

Carbon to Nitrogen ratios of soils are reduced, acid forest soils become more acid and microtoxins such as aluminium and manganese are released. These, along with high N, inhibit tree roots and mycorrhizae. They become more susceptible to drought, waterlogging, frost and root rots such as phytophthora.

<u>Fire alleviating canopy water stress</u>

Le et al. (2025) assessed remote-sensed evidence of fire alleviating forest canopy water stress under a drying climate in jarrah forests in Western Australia:

*We observed that, depending on fire severity, the reduction in water stress persisted for 7–8 years following low-severity prescribed burns and more than 20 years after high-severity wildfires. These findings suggest a role for PB in alleviating water stress, and that PB (*prescribed burns*) can serve as a strategic tool for water stress mitigation particularly with the advent of climate change.*

<u>Changes in water potential, hydraulic conductance, water deficits, water stress and stress signalling</u>

Jurskis et al. (2005) link parasite outbreaks to fire exclusion and soil eutrophication, showing how altered conditions favour mistletoes, cherries, and pathogens in declining forests. A very useful discussion centres around the higher water potential and higher levels of nutrients and water in unhealthy trees might favour the survival and recruitment of mistletoes.

Nolan et al. (2021) found that declining in the soil–root pathway exacerbates plant water deficits, increasing the likelihood of xylem embolism and canopy dieback during drought. They emphasise that canopy dieback does not always equate to mortality in eucalypts, but recovery capacity may be limited by carbohydrate reserves and vulnerability to insect attack.

Moore (2012) provides useful information in this document "Flooding following Drought: a Swift and Subtle Killer of Stressed Trees Tree Health and Drought, Tree Roots, Trees and Water, Water Stress". The paper provides useful tree response information and flowcharts on drought, waterlogging and flooding and waterlogging following drought.

Moore (2012) proposes a dose model where sequential or compounding stresses, such as drought followed by flooding, can overwhelm tree resilience. He shows that long droughts deplete root carbohydrates and mycorrhizal partners, leaving trees susceptible to fungal disease and mortality when subsequent waterlogging occurs. They note that stressed trees begin to regrow fine absorbing roots and mycorrhizal partners resume growth when soil moisture increases after the dry period.

Brunner et al. (2015 review tree root responses to drought, noting strategies such as biomass adjustments and stress signalling. They emphasise the protective role of mycorrhizas, which enhance hydraulic conductivity and water uptake under drought conditions.

Davison (2016) consider the issue of waterlogging in jarrah forests: Davison attributes jarrah deaths in Western Australia to waterlogging damage, supported by wet decades and tylosed sapwood symptoms.

Section summary

Research demonstrates that exclusion of regular mild fire alters soil moisture, nutrient status, and microbial communities, driving chronic forest decline. Jurskis and Turner (2002), Burrows et al. (2025), and the Forestry Corporation of NSW (2020) show that fire absence leads to mulch buildup, wetter soils, and higher pathogen susceptibility, while prescribed burning stabilises soil conditions and reduces canopy stress. Jurskis (2020)) confirms that elevated nitrogen and impaired roots from fire exclusion reduce drought resilience and increase vulnerability to waterlogging. Le et al. (2025) provide remote-sensed evidence that prescribed burns alleviate canopy water stress for up to two decades, highlighting fire as a strategic tool under climate change. Together, these findings underscore that mild fire maintains soil balance, root health, and canopy resilience, while its absence fosters decline through altered soil physics and physiology.

Other research highlights how soil-driven changes cascade into tree stress responses. Perry (1982) and Castano et al. (2019) highlight the critical role of fine feeder roots and ectomycorrhizal fungi in sustaining crown health and mitigating drought stress, both disrupted by fire exclusion. Bobbink et al. (2010) highlight globally that nitrogen accumulation alters root–shoot ratios and mycorrhizal infection, reducing resistance to drought, frost, and pathogens. Nolan et al. (2021) link soil root pathway decline to xylem embolism and canopy dieback, while Moore (2012) demonstrates how sequential stresses such as drought followed by flooding, overwhelm resilience by depleting root carbohydrates and symbiotic partners. Brunner (2015) and Davison (2016) further confirm that impaired drainage and waterlogging exacerbate mortality risks. Collectively, these studies reveal that soil changes from fire exclusion destabilize root physiology, water relations, and stress signalling, making forests increasingly vulnerable to compounding climate and biotic pressures.

2.4 Forest decline, fire, soil, soil nutrient and soil physical changes across the world

This section explores forest decline, fire, soil, soil nutrient and soil physical changes across the world

Consideration of this issue by individual authors

Jurskis (2020) classifies decline into predisposing (genetics/site, including frequent mild fire), inciting (human disturbance), and contributing (biotic responses). He stresses that chronic decline arises when fire exclusion alters soils, triggering stress cascades that pests and competitors exploit.

Jurskis (2004 a) highlights that fire exclusion alters soil and leaf chemistry, disrupting root–fungal symbioses and promotes root pathogens and arbivory, thereby accelerating decline.

Turner and Lambert (2005) link dieback (actually decline) in eastern NSW eucalypt forests to nutritional imbalances, including long-term nitrogen accumulation and imbalances in soil, which have negative impacts on roots and mycorrhizae. They highlight that burning and grazing stabilise nitrogen pools, while water stress compounds vulnerability, with symptoms lagging years behind soil changes. Turner and Lambert also describe a three-stage nitrogen cycle in forests, where fire absence drives nitrogen accumulation and saturation, lowering C:N ratios and destabilising tree health. Regular burning maintains equilibrium and prevents decline.

Jurskis et al (2011) highlights that studies of frequent burning in eucalypt ecosystems showing that accumulation of N in the absence of fire drove changes in their composition, structure and function.

Turner et al. (2008) highlight important points, included here due to the important information provided:

- *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.

Turner et al. (2008) calculate that a 5-year fire cycle balances nitrogen inputs and losses, stabilising soil chemistry and supporting eucalypt health, though soil fertility modifies the optimal interval.

Jurskis (2005 b) get to the root of the tree decline issue “It appears that chronic abiotic stress causes tree decline when the function of roots is impaired by changes in soils”. As he notes in this review, feeder roots and mycorrhizae degenerate before the onset of above-ground symptoms.

Jurskis (2011 a) shows that long-unburnt eucalypt sites accumulate nitrogen, aluminium and acidity, leading to canopy death, while frequently burnt plots maintain healthier crowns and more stable soil chemistry. He also notes the changes in soil condition described in declining eucalypt forest are similar to those causing decline in many forests and woodlands around the world where high levels of nitrogen accumulate as a result of industrial emissions.

Jurskis and Turner (2002) note that the reduced application of low- intensity fire with eucalypts is a common agent of changed soil conditions, including soil moisture and nutrient status. Jurskis and Turner (2002) also outline a model in relation to changed land management, site changes (including increased organic matter and nitrogen), primary biotic responses and secondary changes:

Jurskis (2020) outlines critical information in relation to changes in soils In the absence of burning and/or grazing:

In eucalypt forests and woodlands, burning and/or grazing of native pastures maintains sunny, airy, warm and dry topsoils and natural nutrient cycling processes which support mature trees, herbs and grasses. In the absence of burning and/or grazing, soil physics and chemistry change and vegetation responds, reinforcing the changes. Mulch, rank herbage or woody understorey builds up, sunshine and air circulation are reduced. Nitrogen in litter, seedlings and herbage that had previously been volatilised by fires and returned to the atmosphere, or mineralised by fires and taken up by the flush of new growth, now accumulates in the soil and dense rank growth or developing shrubbery. Topsoils become cooler, damper, softer and deeper.

Carbon to Nitrogen ratios of soils are reduced, acid forest soils become more acid and microtoxins such as aluminium and manganese are released. These, along with high N, inhibit tree roots and mycorrhizae. They become more susceptible to drought, waterlogging, frost and root rots such as phytophthora. The deteriorating soils and roots cause nutrient imbalances, particularly in N:P ratios, and physiological changes in the trees. New leaves are aborted before they mature and there is ongoing recycling of epicormic shoots. Thin canopies and sick roots promote scrub invasion. Trees’

sapstreams and foliage become more attractive and nutritious to arbivores – that is anything that derives nutrients from any part of the tree including roots, sapwood, sap and leaves.

St Clair and Jurskis (2010) argue that excluding frequent low-intensity fire results in physical and chemical soil properties, weakens eucalypt roots, and drives chronic decline. This process also builds fuel loads and alters flammability, increasing the risk of catastrophic megafires.

Muqaddas et al. (2015) consider long-term frequent prescribed and surface soil carbon and nitrogen pools in a wet sclerophyll forest of Southeast Queensland, Australia. They note that compared with the unburnt treatment, the 2yrB treatment lowered soil total C by 44%, total N by 54%, HCl hydrolysable C and N by 48% and 59%, KMnO4 oxidizable C by 81%, microbial biomass C and N by 42% and 33%, cumulative CO2-C by 28%, NaOCl-non-oxidizable C and N by 41% and 51%, and charcoal-C by 17%, respectively and the 4yrB and unburnt treatments showing no significant differences for these soil C and N pools.

Landsberg (2006) investigates canopy dieback in Eucalyptus blakelyi and found that insect defoliation was linked to foliage nutritional quality. He concluded that enhanced foliar nutrition in dieback trees was more likely due to benign soil fertility conditions than environmental stress.

Granger et al. (1994) link decline in riparian Eucalyptus camphora and E. ovata stands to excessive nitrogen availability and rising salinity. They found that declining stands were unusually nitrogen-rich, fostering nitrophilous weeds and suggesting ecosystem nitrogen saturation. They identified that nitrogen availability in declining stands was greater than that recorded in other Australian forests, was dominated by nitrification and was extremely variable and that nitrate concentrations in free soil water from declining forest on a dry site were many times those in the corresponding healthy forest.

Ishaq (2014) identify soil chemistry changes, including reduced pH and micronutrient imbalances, as factors predisposing Eucalyptus gomphocephala to decline in WA. Crown health was positively related to Mn, Cu, and Zn, suggesting nutrient stress contributes to dieback.

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) include useful discussion in relation to tree nutrient-availability, including N Cycling, P cycling, soil pH and exchangeable cations.

Grove and Malajczuk (1985) found that understory shrubs in karri stands in WA contained a large proportion of nutrients, especially nitrogen and Sulphur, despite lower biomass. They highlighted the

dominance of Bossiaea laidlawiana in nutrient pools, showing its disproportionate role in forest nutrient dynamics.

Jones and Davidson (2014) show that time since fire strongly influenced soil nutrient dynamics in alpine ash forests in Tasmania, with nitrogen increasing but phosphorus remaining limited. They argue that prolonged fire absence leads to nutrient imbalances, shrub thickening, and competitive disadvantage for eucalypts.

Ellis et al. (1980) find that burning, not just felling, restored growth in high altitude alpine ash suffering dieback in Tasmanian alpine ash forest. Periodic controlled burns improve tree health and growth rates over more than a decade.

Ellis (1971) attributes alpine ash mortality in Tasmania to cooler, moister soils caused by rainforest understory invasion. He proposed a simple dieback model linking increased soil moisture and nitrogen to root stress, folivory, and fungal pathogenicity.

Bobbink et al. (2010), in an invited feature article published by the Ecological Society of America and synthesising a “global assessment” succinctly summarise the process underlying chronic tree decline:

…..In eucalypt forests and woodlands, burning and/or grazing of native pastures maintains sunny, airy, warm and dry topsoils and natural nutrient cycling processes which support mature trees, herbs and grasses. In the absence of burning and/or grazing, soil physics and chemistry change and vegetation responds, reinforcing the changes. Mulch, rank herbage or woody understorey builds up, sunshine and air circulation are reduced. Nitrogen in litter, seedlings and herbage that had previously been volatilised by fires and returned to the atmosphere, or mineralised by fires and taken up by the flush of new growth, now accumulates in the soil and dense rank growth or developing shrubbery. Topsoils become cooler, damper, softer and deeper.

Dijkstra and Adams (2015) undertake a meta-analysis which demonstrates that fire helps balance nitrogen and phosphorus in woody plants across the world, sustaining productivity and resilience in fire-affected ecosystems worldwide. They 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.

Adams et al. (2004) consider soil functional responses to excess nitrogen inputs at a global scale:

Attiwill and Adams (1993) undertake a broad world view of nutrient cycling and decomposition in forests.

Hevia et al. (2019) use dendrochemistry to show that declining silver fir and Scots pine trees had lower growth, higher wood density, and nutrient imbalances. They propose Mn ratios (Ca:Mn, P:Mn) as early-warning signals of drought-induced dieback decades before growth decline. They find that declining trees presented lower radial growth rates and higher earlywood wood density than Non Declining trees, but these differences are more pronounced and started before in silver fir than in Scots pine.

Section summary

Research consistently shows that exclusion of regular mild fire disrupts soil chemistry and physical properties, driving chronic forest decline. Jurskis and Turner (2002) highlight that fire absence leads to nitrogen accumulation, reduced C:N ratios, increased acidity, and release of toxic elements such as aluminium and manganese, all of which impair roots and mycorrhizae before canopy symptoms appear. Turner et al. (2008) provide valuable research in relation to increased nitrogen and changes in soils over time. Turner and Lambert (2005) demonstrate that nitrogen saturation destabilises tree health, with a five-year fire cycle balancing inputs and losses to sustain eucalypt resilience. Case studies across Australia confirm that long-unburnt sites develop cooler, wetter soils, dense shrub layers, and nutrient imbalances, fostering pests, pathogens, and arbivory.

As highlighted above, other studies by Jurskis (2004 a, 2005 b, 2011 a and 2020), Jurskis et al (2011), St Clair and Jurskis (2010), Ellis (1971), Landsberg (2006) and Muqaddas et al. (2015) highlight that exclusion of frequent low-intensity fire results in changes in physical and chemical soil properties and a number of associated changes.

This process is echoed globally. Dijkstra and Adams(2015) highlight that fire maintains nutrient balance in woody plants worldwide, while Bobbink et al. (2010) synthesise that fire exclusion universally alters soil physics, nutrient cycling, and vegetation structure, reinforcing decline and increasing megafire risk.

Complementary studies emphasise the broader soil, nutrient and tree health nexus. Close et al.(2011) and Ishaq (2014) link eucalypt decline in Western Australia to micronutrient imbalances, with prescribed fire improving availability of Mn, Cu, and Zn and enhancing crown health. Granger et al. (1994) and Landsberg (2006) highlight that excessive nitrogen fosters dieback and insect defoliation, while Ellis demonstrates that burning restores alpine ash growth by correcting soil moisture and nutrient stress. Muqaddas et al. (2015) quantify how frequent burning reduces soil carbon and nitrogen pools, stabilising nutrient cycling. Globally, Adams et al. (2004) caution that nitrogen additions reshape species composition in low-phosphorus ecosystems, while Hevia et al. (2019) identify dendrochemical nutrient ratios as early warning signals of drought-induced dieback.

Together, these findings support the conclusion that mild fire is essential for maintaining soil equilibrium, root function, and long-term forest health, with Australian research leading the way in demonstrating these links in relation to the importance of regular mild fire.

2.5 Forest decline, fire, soil, fungi and mycorrhizal changes across the world

This section explores forest decline, fire, soil, fungi and mycorrhizal changes across the world

Consideration of this issue by individual authors

Horton (2011) and Horton et al. (2013) undertake important research in relation to ectomycorrhizal (ECM) fungal communities. Horton et al. (2013) note “altered soil chemistry associated with eucalypt forest decline mediates changes in the ECM fungal community”.

Horton et al. (2013) undertake research with major findings in relation to ectomycorrhizal fungi in Tasmania:

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.

Horton et al (2011) note:

This study corroborates northern hemisphere studies which show that changes in soil chemistry, especially mineral nitrogen, can strongly influence mycorrhizal species’ richness, community structure

and composition. It is the first study to find a strong correlation between ectomycorrhizal fungal communities and the status of eucalypt forest health. The results support the currently proposed model that, in the absence of fire, premature decline of temperate Australian eucalypt forests is closely linked to changes in soil chemistry, understorey vegetation and mycorrhizal communities.

Horton et al. (2011) note that Eucalypt health is probably not maintained by an isolated single fire event but a series of fire and or disturbance events, with specific intensities and intervals.

The research by Horton et al. is world class.

Shen et al. (2016) demonstrate that frequent fire (every 2 years) in an Australian wet sclerophyll forest increased soil bacterial diversity but not abundance. Fire frequency alters bacterial community structure, with soil pH and C:N ratio as key drivers in the most frequent fire treatment (B2), while other factors (EC, DOC, DON, MBC, NH4+, TC and TN) were significant in the less frequent burning and no burning treatments (B4 and B0).

Importantly, the above authors had considered fire issues in their studies.

Castano et al. (2019) provide important 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))*

In summary, Castano et al. (2019) emphasise the critical role of ECM and AM fungi in nutrient uptake, drought alleviation, and ecosystem functioning. Eucalyptus species host both ECM and AM fungi, with shifts in soil chemistry altering their balance and impacting forest health.

Adams et al. (2006) highlight that Eucalypts have been shown to form both arbuscular mycorrhizas (AM) and ectomycorrhizas (ECM) in glasshouse experiments. They note that adult E. grandis trees sampled in situ were invariably heavily ectomycorrhizal, with 76–100% fine root length colonised (% RLC).and comparatively low levels of AM, with typically less than 10% RLC.. They note that the current research suggests that arbuscular mycorrhizas are more prominent on seedlings, whereas ectomycorrhizas predominate in adult trees of E. grandis.

Findlay et al. (2023) emphasise the critical role of mycorrhizal fungi in mitigating stress in eucalypts, particularly ectomycorrhizae which dominate mature trees. They note that ECM improves water uptake, root biomass, and pathogen defence, but causality between ECM presence and tree health remains unresolved.

Findlay et al. (2023) also note:

In Eucalyptus species, both improved and declining tree health may be associated with ECM presence. Ishaq et al. (2013) demonstrated the importance of mycorrhizae presence in mitigating stress faced by Eucalyptus gomphocephala (tuart) seedlings. Examining the proportion of ECM and arbuscular (AM) fungi colonisation, the authors found a 'probable link' between increased ECM presence and healthier tree canopies (Ishaq et al. 2013). This work is supported by Scott et al. (2013), who found that declining E. gomphocephala seedlings had significantly lower fine root counts and ECM presence. Horton et al. (2013) also concluded that ECM species richness was lowest where Eucalyptus delegatensis (alpine ash) was severely declining. Thus, improved tree health can predict increased ECM composition within host roots. However, it is unknown if greater ECM presence is linked to better tree health – or, conversely, if lesser ECM facilitates dieback, or even if dieback is linked to a decline in ECM composition (Sapsford et al. 2017). For instance, inoculation of ECM colonies in Castanea (chestnut) improved plant growth and recovery from water stress (Aryal et al. 2021). Addressing this causality dilemma will aid in understanding how ECM presence may mitigate dieback.

Scott et al. (2013) note that 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 and seedling survival, height and foliar health were significantly correlated with the crown health of the adjacent woodland trees. Seedling survival is also significantly correlated with the ectomycorrhizal TDS of the adjacent woodland trees.

Scott et al. (2012) note that Eucalyptus gomphocephala crown decline was significantly positively correlated with fine root and ectomycorrhizal density and trees with declining crowns had significantly fewer fine roots and ectomycorrhizal mats.

Bunyard (2020) highlight the prevalence of dual-mycorrhizal plants, including many eucalypts, which can host both AM and ECM fungi. He emphasises the competitive and "duelling" dynamics between mycorrhizal types, drawing on Teste et al. (2020). Bunyard (2020) also highlights a considerable number of dual-mycorrhizal plants or duelling mycorrhizal fungi in their publication using Teste information. This includes many species of Eucalypts, Acacia, Allocasuarina, Casuarina, Pultenea and many other species.

Adjoud-Sadadou and Halli-Hargas (2017) confirm the dual symbiotic habit of eucalypts, with AM dominating seedlings and ECM replacing them in older trees. Their study across Algerian plantations shows seasonal and age-related shifts in mycorrhizal colonization.

Kariman et al. (2012) assess jarrah seedlings and found that both arbuscular and ectomycorrhizal fungi improved growth and nutrient uptake, though responses varied by species. They observe that some fungi, such as A. occidentalis, provided functional benefits without forming typical mycorrhizal structures.

Eagar et al. (2022) show that different mycorrhizal associations (AM vs. ECM) alter litter decomposition, nutrient cycling, and soil organic matter dynamics. They argue that ECM-associated soils generally have lower nitrogen availability, influencing broader plant–soil interactions.

Egidi et al. (2019) identify globally dominant soil fungi, mostly gene and mapped the seralist Ascomycota, with traits enhancing stress tolerance and resource uptake. These fungi play key roles in ecosystem resilience and global soil functioning. They identify that whole-genome comparisons with less dominant, generalist fungi point at a significantly higher number of genes related to stress-tolerance and resource uptake in the dominant fungi, suggesting that they might be better in colonising a wide range of environments.

Averill et al. (2018) find that nitrogen pollution favors AM trees over ECM trees, reducing soil carbon stocks. This shift in mycorrhizal dominance may weaken forest carbon sequestration capacity under future nitrogen deposition.

Ma et al. (2023) show that AMF diversity is strongly shaped by soil phosphorus and latitude, while abundance is driven by phosphorus and pH across the globe. They note that soil available P and pH

were the main predictors of the global distribution of AMF abundance. These global patterns highlight AMF's role in ecosystem functioning under global change.

Jo et al. (2019) map tree mycorrhizal associations across the U.S., finding AM tree dominance linked to higher soil C and N stocks. They find that AM tree dominance was positively associated with both soil C and N stocks, particularly for temperate forests, but note that soil C:N ratio was negatively associated with AM tree dominance. Shifts toward AM dominance may accelerate nutrient cycling and alter forest carbon dynamics in eastern USA.

Lin et al. (2016) synthesise global data showing systematic differences: AM forests cycle mineral N rapidly and store more mineral soil carbon, while ECM forests rely on organic N and accumulate forest floor carbon. Mycorrhizal type predicts nutrient cycling but not carbon fluxes alone. They suggest that mycorrhizal type may be useful in predicting how different tree species respond to multiple environmental change factors.

Phillips et al. (2013) contrast ECM fungi (a diverse group of fungi from multiple phylogenetic groups and nearly all of which associate with trees.), which slowly turnover and mobilize organic N, with AM fungi (a monophyletic, species-poor group of fungi which associate obligately with c. 80% of all land plants, most of which are grasses), which rapidly colonize soils and specialize in phosphorus and inorganic N uptake. These differences underpin contrasting nutrient economies in forests.

Teste et al. (2019) document widespread dual-mycorrhizal plants, including Eucalyptus and Acacia, capable of switching between *arbuscular mycorrhizal* AM and *ectomycorrhizal* ECM associations. They identify a large number (89 genera within 32 families) of confirmed dual-mycorrhizal plants within the same plant species and mycorrhizal switching occurs under a wide range of abiotic and biotic factors, including soil moisture and nutrient status. This flexibility offers ecological advantages and potential for restoration in nutrient-stressed environments.

Section summary

Research shows that exclusion of regular mild fire profoundly alters soil chemistry and fungal communities, driving chronic forest decline. Horton et al. (2011, 2013) demonstrate that long-unburnt eucalypt forests accumulate nitrogen, reduce pH, and shift from nitrogen to phosphorus limitation, disrupting ectomycorrhizal (ECM) fungal diversity and reducing species richness. These changes weaken nutrient uptake, particularly phosphorus, and diminish tree health, with declining crowns linked to fewer fine roots and ECM associations (Scott et al. 2012, 2013). Frequent fire, by contrast, stabilises soil chemistry and supports diverse microbial communities, as Shen et al. (2016) show in wet sclerophyll forests. Considered together, these findings highlight that fire maintains balanced soil–fungal interactions essential for resilience, while its absence fosters decline through altered nutrient cycling and weakened symbioses.

Other studies emphasise the dual role of arbuscular mycorrhizal (AM) and ECM fungi in eucalypt health. Castano et al. (2019) and Adams et al. (2006) note that seedlings often rely on AM fungi, while mature trees are dominated by ECM, which enhance drought tolerance, nutrient uptake, and pathogen defence. Research by Findlay et al. (2023), Ishaq et al. (2013), and others confirms that healthier crowns correlate with greater ECM presence, though causality remains unresolved.

Global syntheses (Lin et al. 2016; Phillips et al. 2013; Averill et al. 2018) show that AM and ECM forests differ systematically in nutrient cycling and carbon storage, with nitrogen pollution favouring AM dominance and reducing soil carbon stocks. Teste et al. (2019) and Bunyard (2020) highlight widespread dual-mycorrhizal plants, including eucalypts, capable of switching associations under stress, offering ecological flexibility.

The evidence supports that fire regimes and mycorrhizal dynamics jointly underpin forest health, with disruption of either leading to decline.

3 Importance of regular mild fire and adaptive management to maintain and restore forest health and reduce forest decline across the world

This section explores the importance of regular mild fire and adaptive management to maintain and restore forest health and reduce forest decline across the world.

Jurskis and Underwood (2015) highlight the importance of adaptive management and argue that forest management has regressed from pragmatic adaptive fire use to theory-driven approaches, leading to forest decline. They emphasise that resources should be redirected from disaster response and academic research toward practical adaptive management and restoration.

Jurskis (2011 a) highlights the importance of prescribing burning programs and highlight they are essential for forest nutrition and health, with Western Australia demonstrating and consistent use. Adaptive management combining burning, thinning, and other practices is urgently needed in eastern Australia to restore resilience. They highlight that 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.

Jurskis (2020) notes that Forestry Corporation recognize chronic eucalypt decline caused by fire exclusion and are ready to apply adaptive management and monitoring rather than continuing with further research.

Jurskis and Turner (2007) highlight the assumption that non-intervention in reserves ensures sustainability, showing that active management often better meets ecological and socioeconomic goals. Their analysis suggests prioritizing management across all forests rather than simply expanding reserves. They suggest that it may be appropriate to place less priority on establishing new reserves and more priority on management in all public forests.

Jurskis and Black (2019) in their poster “Landscapes must be managed” highlight frequent mild burning makes ecosystems healthy and safe.

Burrows et al. (2025) make observations of fire regime, overstorey tree canopy decline in karri forests and forest health and the importance of adaptive management: They observe that long-unburnt karri forests suffer canopy decline and reduced resilience and recommend reintroducing frequent mild fires to improve forest health and protect communities from damaging bushfires under climate change.

South East Timber Association website (2023) in their valuable document “Use of Fire to Improve Native Forest Ecological Health” outline a number of case studies in SE Australia on the importance of regular mild burning maintaining forest health, yet again highlighting the importance of adaptive management.

Muqaddas et al. (2015) consider long-term frequent prescribed and surface soil carbon and nitrogen pools in a wet sclerophyll forest of Southeast Queensland, Australia. Their study found that prescribed burning every four years sustains soil carbon and nitrogen pools, making it a more sustainable management practice for subtropical wet sclerophyll forests.

Forestry Corporation of NSW (2020) note the importance mild fire and thinning to reduce eucalypt decline, it is great that a land management organisation understands the issue:

Eucalypt decline can be effectively managed at the landscape scale by reinstating and maintaining more frequent low-intensity fire regimes. This aims to reduce the mesic understory that has increased in density and extent in recent decades through reduced fire in the landscape, which has led to increased soil moisture and higher susceptibility to soil borne pathogens. Competition between trees is another factor which can lead to stress and increase the susceptibility of trees to disease and insect attack. Thinning (selective removal of some trees) stands of trees in some forest types can be used to reduce competition and lower the likelihood of disease, insect attack and drought stress. Overall, there are strong linkages between canopy health, fuel management, fire risk and silviculture in many forest types. The implementation of frequent low intensity fire regimes in these types can provide multiple benefits.

Franz (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.

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

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.

A media release by Forestry Australia (2021) highlights the importance of active and adaptive forest management as a key to addressing ecosystem decline. They note that active and adaptive forest management key to addressing ecosystem decline and any response to the challenge of restoring and maintaining forest ecosystem health and resilience must include active and adaptive management of all forests, across all land tenures to address these threats. This includes year-round management actions such as promoting and supporting forest health and diversity, more strategic fuel management interventions, maintaining roads for access and protection as well as intervention to manage pests and diseases are all critical aspects in need of attention. They note the need proactive management of fire risk including strategic use of prescribed burning, maintaining forest access including strategic fire breaks and mechanical interventions such as thinning where appropriate and a shift forest conservation strategy from creating more protective areas to a broader strategy of targeted management actions designed to specifically address major threats to our forests and biodiversity.

In relation to adaptive management opportunities for Australia, O'Donnell (2022) summarises the US Forest Service's wildfire crisis strategy (Confronting the Wildfire Crisis A Strategy for Protecting Communities and Improving Resilience in America's Forests and associated documents), emphasising large-scale proactive treatments, prescribed fire, and collaborative management across jurisdictions. The plan aims to restore resilience, reduce wildfire risk, and treat millions of acres over a decade. O'Donnell notes that in Australia there is totally inadequate funding, focus and commitment for reducing fuel loads, undertaking prescribed burning, forest thinning and community protection.

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. (20021) highlights current fire strategies need to change from the suppression focus:

….recapturing the once extensive influence of the low- and moderate-severity fires that shaped and maintained these ecosystems for millennia requires a paradigm shift from strategies favoring fire suppression to those favoring fire-adapted forests and communities (reviewed by Hessburg et al. 2021, Prichard et al. 2021).

Section summary

Collectively, these findings support the conclusion that mild fire and adaptive management are essential to maintain soil equilibrium, root physiology, and long-term forest resilience.

Authors who highlight the importance of adaptive management across the world for forest decline, including regular use of regular mild fire, are outlined above and include Jurskis, Turner, Burrows, Muqaddas, Hessburg, Hagmann and a number of other world authors and the South East Timber Association, Forestry Corporation of NSW, US Forest Service and 20-Year Forest Health Strategic Plan for Eastern Washington.

4 Conclusions

Published research work by a number of experienced researchers clearly shows that a large amount of research has been completed in relation to forest decline across the world, including eucalypt decline, and decline in forest health associated with changed fire and grazing regimes.

The author considers that exclusion of frequent low intensity mild fire as a primary cause of forest decline in native forests across the world. Based on considerable evidence, the author believes that changed soil processes are the hidden drivers of forest decline. Exclusion of regular mild fire destabilises nutrient cycles, alters soil physics and chemistry, and undermines the root–mycorrhizal foundation of forest health. Above-ground symptoms (crown thinning, pest outbreaks) are consequences of these below-ground changes.

Research across Australia and globally shows that exclusion or lack of regular mild fire has profoundly altered forest ecosystems, driving forest decline in forests and fire-adapted species. Authors such as Jurskis, Burrows, and Forestry Corporation of NSW highlight that reduced low-intensity burning leads to soil nutrient imbalances (particularly nitrogen accumulation), dense understories, weakened tree physiology, and heightened susceptibility to pests, parasites, and arbivory. These changes increase fuel loads, making forests more vulnerable to severe, less controllable wildfires.

Evidence from long-term experiments and case studies demonstrates that human management decisions, including fire suppression, grazing exclusion, fertiliser use, and conservation policies, are the primary drivers of forest decline. Research highlighted above underscores that frequent, low-intensity fire is essential for sustaining nutrient cycles, structural diversity, and long-term forest health, and that its absence has led to widespread decline and heightened ecological imbalance.

Research across multiple regions demonstrates that the absence of regular low-intensity fire is a major driver of forest decline, balanced ecosystems and forest health. Overall, the evidence converges on the importance of mild fire and soil processes in maintaining forest resilience, biodiversity, and long-term health.

Research demonstrates that exclusion of regular mild fire alters soil moisture, nutrient status, and microbial communities, driving chronic forest decline. Collectively, research studies highlighted above reveal that soil changes from fire exclusion destabilize root physiology, water relations, and stress signalling, making forests increasingly vulnerable to compounding climate and biotic pressures.

Research consistently shows that exclusion of regular mild fire disrupts soil chemistry and physical properties, driving chronic forest decline. Research findings support the conclusion that mild fire is essential for maintaining soil equilibrium, root function, and long-term forest health, with Australian research leading in demonstrating these links.

Research shows that exclusion of regular mild fire profoundly alters fungal communities through changes in soils, driving forest decline. The evidence supports that fire regimes and mycorrhizal dynamics jointly underpin forest health, with disruption of either leading to decline.

Collectively, these findings support the conclusion that regular mild fire and adaptive management are essential to maintain soil equilibrium, root physiology, and long-term forest health and resilience.

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