

# Soil and nutrient processes related to eucalypt forest dieback

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## Summary

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. Water stress tends to exacerbate dieback but there is no evidence that it is a primary cause. 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.

*Keywords:* nitrogen; nutrition; nutrient cycling; herbivores; *Eucalyptus*; Australia

## Introduction

Dieback of crowns has been observed to be developing in extensive areas of native eucalypt forest along the east coast of Australia over all land tenures (Ward and McKimm 1982; Stone 1999; Jurskis and Turner 2002; Department of Environment and Conservation 2005). While it has often been noted that insects and other organisms are related to tree damage, it appears they are secondary agents and that other processes are predisposing trees to such damage. One proposition is that the predisposition is a result of changes in soil nutritional status, alone or in conjunction with soil moisture, and such changes directly impact on the trees (Jurskis and Turner 2002).

Relatively little experimental or research work has been designed and undertaken specifically in relation to dieback. However, it is possible to observe characteristics and identify possible processes,

and test these against existing information. The present paper focuses on relationships between soils and nutritional factors and eucalypt dieback.

## Key characteristics of dieback

Key characteristics of dieback in eucalypt stands have been described (e.g. Jurskis and Turner 2002; Jurskis 2005) and while variation exists in the characteristics of dieback across stands and sites, there is commonality. Within individual tree crowns, dieback commences as loss of foliage, followed by dieback of small branches in conjunction with re-sprouting from epicormics. As the process continues, a larger component of foliage is composed of epicormic growth, the crown becomes very thin and dead branches are significant. The final stage of the dieback is crown and tree death.

Descriptions of dieback rarely mention or imply either nutrient deficiency or elemental toxicity symptoms such as interveinal chlorosis, pale green foliage or browning of the leaf edges. While some small areas have been noted as having yellowing foliage which is related to elevated soil pH, trace element deficiency and some salt scorching, these areas are very limited in extent. Dieback varies over time, with increases in intensity in some years sometimes followed by a period of regrowth, but overall there is a pattern of long-term deterioration. The increased intensity of dieback in some areas has occurred in conjunction with drought but it is also noted that drought is not the primary cause.

There are spatial patterns associated with the dieback and there are variations in the degree and rate of development according to soil type. Notably, for example, forest on well-structured, deep soils such as those developed from basalts, is essentially unaffected. Where forests are on soil types which are affected, stands on lower slopes and gullies are the first to show symptoms, followed by progression upslope.

The level of dieback is affected by community structure and composition. While dieback has affected a very wide range of species, the rate and intensity are variable. Notably, the level and rate of understorey development are critical components and are intensified where moist shrubs and vines are involved. Some exotic understorey species (e.g. *Lantana camara*) appear to exacerbate the development of dieback. Dieback becomes noticeable when stands are at least several decades old, and hence

this form of dieback is not usually observed in younger forests or plantations. Insects, parasites and folivores are secondary agents causing intensified crown loss.

Overlying the site and stand characteristics is the history of forest management. Most notably, crown dieback is not obvious in regularly burned and/or grazed eucalypt forests. Regular burning refers to relatively low-intensity fires which irregularly burn parts of the landscape, changing understorey structure and modifying litter.

### Nutrient immobilisation in biomass

Dieback develops over time and varies according to the soil type. In the absence of specific events or climatic changes consistent with causing stress in trees, it is proposed that the causative process is associated with changes in soil nutrient availability. There are two broad possibilities for these changes. The first is that nutrients become immobilised in biomass as stands develop, leading to reduced soil-nutrient availability and consequent nutrient stress. The second is related to an increase in availability of a nutrient leading to changes in nutrient balances and physiological stresses. Such stresses would then lead to predisposition to insect or other infestations.

In the case of nutrient immobilisation in plant biomass, the rate and amount of immobilisation vary according to species and the quality (rate of growth) of that species. Additionally, some species accumulate large quantities of specific nutrients in components of their biomass. For example, high levels of calcium are accumulated within the biomass of smoothed-bark eucalypts, particularly within the bark (Lambert 1981; Tandon *et al.* 1988; Spangenberg *et al.* 1996; Turner and Lambert 2005). This accumulation leads to a significant reduction in available calcium in the soil as the stand increases in age (van Oyen and Charley 1983; Lambert and Turner 1991). Lambert and Turner (1991) reported that by age 27 y, *Eucalyptus grandis* had accumulated, within its biomass, 70% of the total calcium in the ecosystem (to a depth of 1 m in the soil), and this was increasing with further growth. There have been similar patterns, but at a lower intensity, for other elements such as potassium. However, even where such patterns have been measured, there has been no relationship with dieback, and no development of any nutrient deficiency symptoms.

The main patterns in calcium have been measured in species in the subgenus *Symphyomyrtus*, such as *E. grandis* and *E. globulus*. *Corymbia maculata* is also a species with a high level of calcium in the bark and a large accumulation of calcium in tree biomass, but this is generally considered one of the species less susceptible to dieback. While other nutrients are immobilised in biomass to various degrees with increasing stand age, there is no evidence that this process leads to reduced nutrient availability of key elements, in particular phosphorus, within the soil. As an example, 21 kg ha<sup>-1</sup> of phosphorus was immobilised in tree biomass in a mature mixed eucalypt forest in Victoria considered to be of moderate fertility (Stewart *et al.* 1990), and this represented about 3% of the total phosphorus capital. This immobilisation, and even its removal from the site, would not have an affect on soil phosphorus availability. Further, in nutrient assessments of native eucalypt forests, foliage nutrients have not been detected or reported in the literature at deficiency concentrations. Deficiencies

have been noted and reported in *Eucalyptus* plantations but they have been in young stands, not related to crown dieback, and unrelated to nutrient immobilisation in biomass.

Considering the range of sites and species associated with dieback, it is concluded that there is no relationship between nutrient immobilisation in biomass leading to soil depletion and subsequent dieback problems, and induced nutrient deficiency. This does not imply such a process could not occur, particularly under intensive plantation conditions, but there is no evidence to support the proposition that it is leading to the dieback observed generally in eucalypt stands.

### Changes in soil nutrient availability

Nitrogen is a critical nutrient for plant growth and is present in amino acids and proteins. Relatively large quantities of this nutrient are taken up and accumulated within forest ecosystem biomass and the quantities are much larger than is the case for other nutrients. Unlike all other nutrients, nitrogen is not a component of soil parent materials and accumulates over time within ecosystems primarily through processes of nitrogen fixation (either through symbiotic or free living organisms), and inputs from rainfall. Soil nitrogen is predominantly in organic form which is mineralised to the ammonium form, and this is possibly followed by nitrification. Plants take up nitrogen as ammonium ions or nitrate ions or both. The total quantity of nitrogen, the quantity and proportion of each form of nitrogen, and the relative quantities of other nutrients have significant effects on the subsequent growth and health of plants.

Over long periods of time (several decades), and after the period of high nutrient demand during early stand development, it has been reported that both soil total nitrogen and soil mineral nitrogen increase when stands are not affected by fire. The increase in total nitrogen has been noted globally in soils under a range of forest types (Aber *et al.* 1989; Galloway *et al.* 2003) and, when considering the different basic fertility levels of soils being compared, has been quantified in various ways, namely as an increase in the total quantity of nitrogen (kg ha<sup>-1</sup>, or concentration) or as its ratio with another element (such as phosphorus). The relative importance of processes involved in this increase in nitrogen has not been fully quantified but, most plausibly, is partly due to atmospheric inputs and partly to biological fixation. Nitrogen sources from atmospheric inputs in Australia are comparatively low but potentially significant. For example, the coastal areas of NSW have annual inputs of between 1 and 10 kg N ha<sup>-1</sup> y<sup>-1</sup> in rainfall (Turner *et al.* 1996).

A component of the overall increase in nitrogen in undisturbed stands is due to increases in soil mineral nitrogen, defined as the sum of ammonium and nitrate nitrogen. There are, however, difficulties in comparing information across studies due to different analytical extraction methods and reporting of mineral nitrogen. The data reported in this paper, however, are from extractions at single sampling times and represent a comparative snapshot of mineral nitrogen in soil. Forest stands differ in the relative importance of ammonium and nitrate, i.e. in the level of nitrification. Forest types vary in their rate of production of mineral nitrogen and nitrification, so although processes are similar, the actual quantities of nitrogen vary between forest types.

**Table 1.** Mineral nitrogen concentrations in soils under different ages of rainforest development (Lamb 1980)

Stand age (y)	Mineral N ( $\mu\text{g g}^{-1}$ )	
	Wet season	Dry season
10	18.1	19.1
15	30.1	18.1
43	53.6	31.7
53	50.4	32.4
Undisturbed	70.9	80.1

For example, across forest types in mature forests in Victoria, the total quantity of soil inorganic nitrogen varied between 10 and 41  $\mu\text{g N g}^{-1}$  (Adams and Attiwill 1986), and in Tasmania between 5 and 32  $\mu\text{g N g}^{-1}$  (Adams *et al.* 1989). Soils under rainforests and eucalypt forests with developing rainforest understoreys have high levels of mineral nitrogen and these levels generally increase with time. As an example, Lamb (1980) reported increases in mineral nitrogen with rainforest development (Table 1).

Soils under eucalypt forests, natural or plantations, have been shown to have increases in mineral nitrogen over time and, where there is a long time period, it is proposed that availability increases to levels which lead to stresses within the trees. Increases in mineral nitrogen have been demonstrated in a number of Australian forests. For example, Polglase *et al.* (1992) showed increases in both inorganic and total soil nitrogen with increasing age of *E. regnans* regeneration (six stands ranged in age from 5 to 80 y and an additional stand was about 250 y old). The quantity of soil inorganic nitrogen under the 5-y-old stand (surface soil) was 10.8  $\mu\text{g N g}^{-1}$  and at 80 years was 31.6  $\mu\text{g N g}^{-1}$ , while the total nitrogen in the surface soil had increased from 4.8  $\text{g N kg}^{-1}$  to 8.9  $\text{g N kg}^{-1}$  over the same time period. Over a shorter period in a chronosequence of *E. grandis* plantations (up to 30 y of age plus an older natural stand), Turner and Lambert (2005) reported increases in mineral nitrogen. The variation between such analyses is high, both at a single sampling time representing spatial variability, and also over time, but the changes are consistent. Forest areas, burnt at different times, were also assessed and the data indicated a similar increasing pattern of soil nitrogen with increasing periods of time since a fire. The work of Charley (1985) in moist hardwood forest also supports these findings and shows that low-intensity hazard reduction burns maintained both lower soil mineral nitrogen and lower soil total nitrogen (Fig. 1). The results from a number of eucalypt forest ecosystems suggest that in terms of maintaining a specific species mix and structure, and a healthy ecosystem, a stable nutrient situation is required. Such stability can be maintained through regular low-intensity burning. As stated by various workers (see Chase 2001), many forests which are left undisturbed are not stable, self regulating or maintaining themselves in balance.

Inputs and outputs of nitrogen to the mineral soil (A horizon) were evaluated to ascertain patterns in *E. grandis* and *E. pilularis* (data from Turner and Lambert 2005). Inputs were considered to be from litter decomposition, nitrogen fixation and inputs from roots, while losses were primarily uptake (including immobilisation within litter). The results were compared with other systems.

Three stages were identified 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.

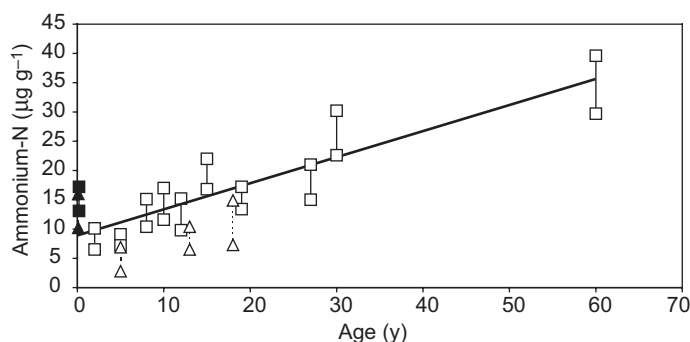
*Stage 2.* Uptake declines and inputs become greater than outputs. Soil nitrogen and carbon accumulate. In the absence of fire, the nitrogen content reaches the initial level. Mineral nitrogen ( $\text{NH}_4^+$  and  $\text{NO}_3^-$ ) increases while the C:N ratio declines. Regular burning minimises the process. The inputs from precipitation are variable as are those from symbiotic nitrogen fixation, being between 1.5  $\text{kg N ha}^{-1} \text{y}^{-1}$  (Hopmans *et al.* 1993) and 4.5 to 7.0  $\text{kg N ha}^{-1} \text{y}^{-1}$  (McColl and Edmonds 1983).

*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.

### Impacts of changes in nutrient availability

Significant effects on root and mycorrhizal development and on plant chemistry have been reported when there are changes in the availability of soil nitrogen. Biochemically, elevated nitrogen in relation to another nutrient such as sulphur, leads to changes in the relative composition of amino acids in foliage and in their concentrations. For example, elevated nitrogen levels (in the absence of associated levels of sulphur) lead to the development of high nitrogen-containing (low-sulphur) amino acids, such as



**Figure 1.** Ammonium-nitrogen concentrations in soils under *Eucalyptus grandis* at different ages (see the squares). Additional data points (triangles) are from native forests, and in their case the age represents years since burning. The solid points represent the unburnt or baseline situation.

arginine, as described by Lambert (1986). Imbalances in plant chemistry can also be exacerbated when trees are under moisture stress due to poor root development or drought and, in this case, can lead to accumulation of the amino acid, proline. These amino acids are attractive key food sources for a range of folivores. Concentrations of amino acids vary depending on different types of stresses and also the age of tissue (Journet and Cochrane 1978), and these processes affect susceptibility to dieback.

There can be differences in insect preference between healthy roadside trees and reference dieback trees (Marsh and Adams 1995). The foliage in the dieback trees had higher quantities of amino acids and the amino acids were in different proportions (in particular, proline) compared with the roadside trees. Marsh and Adams (1995) also demonstrated that both water stress and the form of nitrogen (ammonium or nitrate) had a major impact on the types and quantities of amino acids. Landsberg and Wylie (1983) found that foliage in dieback trees in the rural landscape had higher nitrogen concentrations than trees in healthy forests, while Casotti and Bradley (1991) reported that the concentration of foliage nitrogen in the previous month was positively correlated with the onset of current herbivory, indicating the possibility that herbivorous insects preferentially feed on eucalypt leaves high in nitrogen. Increases in nitrogen or nitrogen saturation within forest ecosystems have been implicated in a number of studies where the health of forest species was reduced (e.g. Granger *et al.* 1994).

Elevated nitrogen availability (in this case applied as fertiliser) has been shown to reduce mycorrhizal development (e.g. Ashton 1976). Root development is affected by changes in nitrogen supply. When nitrate nitrogen is high, there is reduced growth and often darkening of roots, and this is related to the accumulation of aluminium, iron and manganese on the root surface. High concentrations of manganese were found in *E. grandis* on the root surface in conjunction with reduced root development (J. Turner unpublished data) while Neves *et al.* (1982) similarly reported high concentrations of aluminium in four different eucalypt species. The high concentrations in the roots were not reflected in changes in foliage nutrient status and hence the elements were retained in the roots or not translocated. Reduced root development impacts on both water and nutrient relationships.

## Stand structure

Development of the understorey is a critical component of nutrient cycling in stands (Turner and Lambert 2005). The quantity of organic matter cycled and the high concentrations of some nutrients (relative to the overstorey) mean that nutrient turnover is greater than the biomass alone would indicate. The input of relatively low C:N ratio material to the forest floor increases the turnover rate of nitrogen in the forest floor and hence increases nitrogen availability (Turner and Lambert 2005). High concentrations of nutrients were found in foliage of trees disturbed in the Sydney region as a result of suburban development, and they contrasted with much lower concentrations in undisturbed dry sclerophyll species (Lambert and Turner 1987). On deteriorating sites, understorey plants had much greater concentrations of key nutrients, particularly nitrogen and phosphorus, in their tissues (Table 2). When cycled, these tissues increase nutrient availability and exacerbate the nutrient imbalances within the tree component.

## Effects of disturbance

Various types of disturbance occur in forest ecosystems but fire is the most common and is repeated (Attiwill 1994). Fire may vary in intensity from light to extreme with consequent differences in impacts. The focus of many studies has been on the impacts of moderate to high-intensity fires on a large proportion of an area at a single time, while our discussion in this paper focuses on repeated low-intensity fires which affect a moderate and variable proportion of the landscape. The effects of such low-intensity fires are diverse, but, importantly, the nitrogen pool available from litter, soil and understorey is reduced and maintains the forest at Stage 2 as discussed previously. The change in understorey also alters the pattern of nutrient cycling and hence the level of nutrient availability.

Research studies on effects of fire often compare the characteristics of burnt and unburnt areas. Soil nitrogen in burnt areas is reported as lower than in unburnt areas, and conclusions are that fires lead to long-term depletion of nitrogen and reduced productivity (Raison *et al.* 1993). However, in long-term burning studies, such as at Manning River State Forest (Forests NSW, unpublished data held by the Research Division of Forests NSW), the quantity of soil nitrogen in unburnt areas increased whereas that in the burnt areas remained reasonably stable. Guinto *et al.* (1998, 2001) reported on long-term burning studies in Queensland (in excess of 30 y) where nitrogen in soil and litter in regularly burnt sites was lower than in unburnt areas. In a blackbutt (*E. pilularis*) stand, soils in unburnt plots had 0.183% N, while in burnt plots there were long-term levels of about 0.1% N. This would usually be interpreted as long-term depletion due to fire, but the long-term results showed nitrogen accumulation in unburnt areas, ultimately leading to nitrogen saturation (Stage 3).

Recognition of the requirements for regular low-intensity fires to maintain forest health and structure has been reported in a number of studies, some being presented in a model (Benson and Howell 1990).

**Table 2.** Quantities ( $\text{g kg}^{-1}$ ) of nitrogen (N), phosphorus (P) and potassium (K) in foliage in overstorey and understorey in wet and dry sclerophyll forest, and in comparison with disturbed sites (in this case including effects of exotics)

Community	N	P	K
<i>Wet sclerophyll forest on shale soil</i>			
Overstorey	12.3	7.20	6.15
Understorey	16.0	0.99	9.50
<i>Disturbed site on shale soil</i>			
Understorey	21.4	1.54	21.60
<i>Dry sclerophyll forest on sandstone soil</i>			
Overstorey	10.2	0.55	4.63
Understorey	9.7	0.42	6.16
<i>Disturbed site on sandstone soil</i>			
Understorey	13.2	0.68	11.40

## 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 increased predisposition.

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