What’s Killing the Trees?

An investigation of Eucalypt dieback in the Monaro region, NSW

by

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Candidate's Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author’s knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Catherine Ross 30 May 2013
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Abstract

Dieback, the gradual decline in tree health often leading to death, has been identified as an increasing problem throughout Australia and the world. In the Monaro region of NSW, widespread decline of ribbon gums (*Eucalyptus viminalis*) has been occurring over the last 5 to 10 years, and almost all are now dying or dead. The dieback was found to cover an area of around 2000km² between Bredbo, Numeralla, Nimmitabel and Jindabyne; the boundaries are defined by a change in species composition, and it appears that the condition may have spread from a central location around Berridale.

The Monaro dieback has been linked to an outbreak of the eucalyptus weevil (*Gonipterus* sp.), a native to eastern Australia that has become a serious pest in overseas *Eucalyptus* plantations. In its natural habitat however, outbreaks are uncommon and rarely cause widespread damage. To investigate the underlying cause of this outbreak, I conducted a road survey and compared sites with different land uses and fire regimes. I also examined historical climate data to look for patterns or trends over the last 90 years.

Current theories suggest that dieback is the result of ecological simplification due to agricultural practices or a change in fire regimes. In this case, no relationship was found between dieback severity and land use, fire regime, or structural complexity attributes such as understorey density. Methods of managing dieback aimed at improving structural complexity are therefore unlikely to be successful.

The Monaro dieback appears to be related to climate; however the evidence is largely circumstantial and the mechanism that led to the eucalyptus weevil outbreak is still unclear. Over the last few decades, the region’s climate has become warmer and drier, and the distribution of rainfall throughout the year has also changed. This may have an effect on the weevil’s survival, reproduction and phenology, leading to an outbreak. White’s Stress Index and the GROWEST Index also indicate that the climate has become increasingly stressful for the trees. The harsh climate of the Monaro is at the edge of the Ribbon Gums’ climatic range, and the recent drought and changes in climate may have pushed the species beyond a critical threshold.

Under future climate change, it is possible that *E. viminalis* will disappear from the Monaro entirely, resulting in dramatic changes to the landscape and loss of biodiversity. Strategies for rehabilitation may include introducing species from more arid environments to accelerate adaptation to the changing climate.
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List of Abbreviations

ACT  Australian Capital Territory
BMAD  Bell Miner Associated Dieback
GI  Growth Index
GROWEST  Growth Estimation
LI  Light Index
MI  Moisture Index
NSW  New South Wales
SI  Stress Index
SCI  Structural Complexity Index
TI  Thermal Index
TSR  Travelling Stock Reserve
Chapter 1: Introduction

Thousands of tourists travel through the Monaro region of south-eastern NSW every year, heading towards Kosciuszko National Park and the snow fields of the Snowy Mountains. In recent years, the health of eucalypts dotting the rolling grassy plains and rocky outcrops has declined steadily. Many are now dying or dead. This dieback has become a dominant feature of the landscape over the last 5-10 years (Figure 1) and is of increasing concern to both locals and visitors. Similar episodes have occurred in elsewhere Australia and around the world and may be increasing in frequency and severity (Allen, 2009). The cause of dieback often remains a mystery, making management difficult.

The loss of trees on a large scale has serious environmental and social costs. Like much of eastern Australia, the Monaro region has been cleared and grazed for well over a century and as a result much of the native vegetation has been lost or severely degraded. The remaining woodlands and forests represent vegetation communities that are now rare or threatened, and provide important habitat for native species. Nearby areas of high conservation value such as Kosciuszko National Park may also be under threat if the condition spreads. Trees also prevent erosion and salinity and provide shelter for crops, pasture and livestock from freezing and desiccating winds, not to mention their aesthetic value in the landscape. The climate and soils of the Monaro make regeneration slow, difficult and costly, and this could lead to a landscape-scale change in vegetation composition with serious and unexpected consequences.

Figure 1: Dieback on Jindabyne Road. Image: Tim the Yowie Man
1.1 Background

‘Dieback’ and ‘decline’ are general terms referring to a range of conditions affecting trees. These conditions are characterised by a gradual deterioration in tree health over months or years, eventually leading to premature death. At an individual or localised scale this may be of little concern; however when large numbers of trees are affected dieback becomes a serious problem. Dieback is often referred to as a disease of complex aetiology, caused by a combination of biotic and abiotic factors including climatic change or extremes, exotic or native organisms, pollution, land management practices, or natural succession (Old, 2000; Manion, 1981). The term ‘dieback’ can also be used to refer to the sudden death of trees due to acute stress factors such as drought or water logging, and specifically to the fungal disease caused by *Phytophthora cinnamoni* which has caused widespread damage to Jarrah forests in Western Australia (Dieback Working Group, 2013).

The Monaro region is a plateau in the highlands of South East NSW, between the ACT and the Victorian border, with the Snowy Mountains to the west and the coastal escarpment to the east. The high elevation (around 1000m) of the plateau and its position on the leeside of the Snowy Mountains results in a cool and dry climate compared to the surrounding regions. Due to the low rainfall (500-700mm annually), severe frosts and poorly aerated soil, most of the Monaro region is naturally treeless (Jenkins & Morand, 2002; Costin, 1954). However, small pockets of savannah woodland naturally occur on rocky outcrops, with heavier forested areas on isolated hilltops, ranges and in river valleys (Figure 2) (Taylor & Roach, 2003).

![Figure 2: The Monaro plateau, with the Snowy Mountains in the distance. Small isolated patches of woodland are visible in the largely treeless plain. Image: Catherine Ross](image)

Recently, major dieback episodes around Australia have received a considerable amount of attention from scientists, government and the media. Examples include the ‘Jarrah dieback’ in WA mentioned above, ‘high altitude dieback’ in Tasmanian wet eucalypt forests (Ellis, et al., 1980), and ‘bell miner associated dieback’ (BMAD) in sclerophyll forests throughout eastern Australia (Florence, 2005). In the 1980s, northern NSW was also severely affected...
by ‘rural dieback’ (Mackay, et al., 1984). However, very little research has been done in the Monaro region despite the apparent severity and impact of the problem.

Knowledge about the Monaro dieback is largely based on observations from local landholders and preliminary investigation by Neil Murdoch from Sydney University. Murdoch found that the Monaro dieback is species specific; it affects only ribbon gum (*Eucalyptus viminalis*) and to a lesser extent candlebark (*E. rubida*), while other co-occurring eucalyptus species such as snow gum (*E. pauciflora*) and black sallee (*E. stellulata*) remain healthy (Murdoch pers. comm.). He also found that affected trees were heavily damaged by large numbers of leaf-eating beetles and their larvae, which he identified as the eucalyptus weevil (*Gonipterus scutellatus*). The weevil infestation appears to be the ultimate cause of death through repeated defoliation. This conclusion is supported by the effectiveness of stem-injected pesticides in reducing insect-related damage (Murdoch pers. comm., Appendix 1). However, this is an expensive treatment and will not be effective in the long term if the underlying cause of the infestation is not identified and addressed.

In March 2011, Greening Australia held a field day with local landholders to bring together and discuss their observations of dieback and possible management options. This meeting confirmed many of the observations made by Murdoch, and highlighted the concern felt by landholders about the loss of trees on their properties (Appendix 2). Following on from the field day, Greening Australia offered financial and advisory support for this honours project to investigate the problem further. This research will inform Greening Australia’s methods for conservation and rehabilitation of native vegetation in the Monaro region.

1.2 Project Aims
This project will investigate the Monaro dieback, with an aim to increase the current knowledge and identify the most likely cause or contributing factors. The results of this study will inform management practices and may contribute to the understanding of dieback more generally.

1.3 Research Approach
This thesis provides a review of past and current research into dieback across Australia and around the world, resulting in a conceptual model that will help to visualise the complex interactions between factors that may be contributing to the problem. This model was used as the basis for the investigation into the Monaro dieback.
Its extended duration provided the opportunity to retrospectively examine dieback on the Monaro plains. A range of methods were used including the collection of adult weevils and eggs for identification and determination of parasitism rates, a road survey of the affected area, comparative field studies of affected sites with differing land uses, fire regimes and structural attributes, and analysis of historical climate data. Each of these routes of investigation was examined to provide evidence to support or eliminate the many possibilities presented in the literature review.
Chapter 2: Literature Review

2.1 Introduction
Dieback in Australia and around the world has often been associated with chronic defoliation by insects (White, 1969; Mackay, et al., 1984; Landsberg, et al., 1990). The importance of insects in the death of trees affected by dieback has been demonstrated by the successful recovery of trees after treatment with pesticides (Mackay, et al., 1984), and by the observed specificity for tree species as insect hosts (Lowman & Heatwole, 1992). However, it is unclear whether defoliating insects are the cause of tree dieback, or are symptomatic of other underlying biotic or abiotic factors. Nevertheless, the role played by insects in the complex relationships between trees and their environment appears vital to our understanding of dieback, and may provide strategies for the successful management and prevention of dieback in the future.

Eucalypts have extremely high rates of herbivory due to their low nutrient content (Fox & Macauley, 1977). They are also highly resilient to attack as they have the capacity to replace their canopy through epicormic growth from the trunk and branches (Ohmart & Edwards, 1991). However, trees that have been defoliated produce new foliage of superior dietary quality, allowing insect populations to mature and reproduce more quickly (Landsberg, 1990). This sequence may create a feedback effect in which trees are repeatedly defoliated over multiple years until their carbohydrate stores are depleted, eventually leading to death (Mackay, et al., 1984; Landsberg, 1990b) (Figure 3).

![Figure 3: Dieback feedback loop. Repeated defoliation by leaf-eating insects followed by replacement of the crown through epicormic growth eventually leads to tree death.](image-url)
Phytophagous (plant feeding) insects can be classified into different groups according to their feeding preferences and population dynamics. These aspects may be very important in explaining the occurrence of outbreaks. Firstly, insects may be classed by their preferred diet, for example leaf-chewing or sap-sucking. Second, members of these groups may be further classified as either senescence feeders that feed on mature and senescing tissues (e.g. bark borers and some psyllids), or flush feeders that prefer new growth (e.g. chrysomelid beetles, sawflies) (Landsberg & Cork, 1997). It is important to note that different stages of a single species’ life-cycle may exhibit different dietary preferences, and that the two classifications are independent. For example an insect may be a leaf-chewer in the larval stage but swap to a sap-sucker as an adult, and a leaf-chewer may be either a senescence or a flush feeder (White, 2009).

The population dynamics of insects can be classed either as ‘eruptive’ or ‘latent’ (Price, et al., 1990). Eruptive species have a cyclic and often unpredictable ‘boom-bust’ pattern of outbreak. These species are typically generalist feeders and can cause widespread damage. However, outbreaks are usually controlled by exhaustion of the resource, or by ‘top-down’ control by predators or parasites. Some examples include scarab beetles, phasmatids (stick insects) and some psyllids (Landsberg & Cork, 1997). Latent insect species are typically specialist flush feeders where competition for limited oviposition sites maintains low, steady populations. Predators or parasites have little effect in controlling the population (Price, et al., 1990). Most insects that feed on eucalypts may be classified as latent species (e.g. chrysomelid beetles, sawflies) due to the poor dietary quality of adult foliage. Outbreaks of latent species are less common but can cause extensive damage and mortality, and the underlying reasons often remain mysterious.

There are four likely explanations for the high levels of defoliation often experienced by trees suffering from dieback:

- Missing or ineffective parasite or predator
  - This may occur where an exotic insect has been introduced to an area where its natural enemies are absent, or where loss or simplification of habitat, competition with other species, or a climatic factor reduces the diversity and abundance of insectivores and parasitoids.

- Isolation
  - Clearing for agriculture may increase the insect burden on the remaining trees.
• Improved quality or availability of food
  o Tree stress – factors such as soil degradation, exposure, climate, or pollution may put trees in a state of chronic stress, increasing their dietary quality for insects as nutrients are mobilised in senescing leaves and making them less able to recover from defoliation. Senescence feeders are more likely to benefit from tree stress.
  o Tree vigour – trees growing under benign conditions produce abundant foliage of high nutritive value to insects, allowing population growth. This is more likely to benefit flush feeders.

• Direct climatic effects
  o Insect reproduction and development is highly sensitive to climatic conditions, so favourable conditions may increase reproduction or growth rates.

2.2 Explanations for Insect Related Dieback

2.2.1 Missing or Ineffective Parasite or Predator
Parasites and predators often play an important role in controlling insect populations. For example, when introduced to areas where their natural enemies are not present, exotic insects may damage native forests and plantations. For example, sirex wasp (Sirex noctilio) outbreaks have led to mortality in pine plantations since it was introduced to Australia in the 1950s. The wasp is normally controlled by a parasitic nematode. This nematode has been introduced successfully to Australia as a biological control (Kuch, 1994).

In contrast, the loss of native predators in response to habitat loss, competition from other species, or climatic conditions may lead to outbreaks of phytophagous insects.

Loss of habitat may be a particularly important factor where grazing has removed the shrubby understorey that provides food and protection for birds, reptiles, mammals and predatory or parasitic insects (Ford, 1980; Landsberg & Wylie, 1988; Close, 2003; Loyn & Middleton, 1980). In Armidale NSW, Ford and Bell (1981) found that diversity and abundance of insectivorous birds was related to low understorey density and inversely related to the severity of dieback. Restoring understorey diversity is a common management strategy used to combat rural dieback (Nadolny, 2002; Platt, 1999).
Predators can also be driven out by competitors, as in bell miner associated dieback (BMAD). In this instance colonies of bell miners drive out other insectivorous birds, causing outbreaks of psyllids (Florence, 2005; Jurskis, 2005).

Climatic conditions that are detrimental to an insect’s natural enemies may also trigger outbreaks, especially in eruptive insect species with cyclic patterns of outbreak. In a study of cyclic phasmatid (stick insects) outbreaks in the mountains of NSW and Victoria, Readshaw (1964) hypothesised that cool summer conditions reduce numbers of a parasitoid wasp, releasing the phasmatids from control and resulting in outbreak. Drought in the Riverina region of Victoria is thought to cause outbreaks of the gumleaf skeletoniser (*Uraba lugens*) due to suppression of a fungal disease (Farrow, pers. comm.).

2.2.2 Isolation
Isolated trees may experience a greater insect burden than trees in forests or woodlands, due to the greater difficulty for insects to disperse from one tree to the next (Landsberg, et al., 1990). This density dependence has been observed in the New England dieback, where paddock trees were more affected by dieback than nearby trees in remnant forest or woodland (Mackay, et al., 1984), however no evidence for this was found in a study in the Southern Tablelands of NSW where stands of similar density differed significantly in numbers of defoliating insects and tree health (Landsberg, et al., 1990). The apparent density effect may be due to other factors related to land management. For example, trees surrounded by pasture may experience greater numbers of insects such as scarab beetles whose larvae feed on grass roots (Landsberg & Wylie, 1988). Isolated trees are also more exposed to the elements, and may have heavier mistletoe infestations, placing them under greater stress.

2.2.3 Improved Quality or Availability of Food

*Tree stress*
Dieback is usually assumed to be the result of stress (Manion, 1981). Certainly, acutely stressful conditions such as severe drought or inundation can result in widespread tree death within days or weeks. However, chronic decline is more difficult to attribute to a single cause. Trees may be stressed by a range of factors, such as drought, water logging, soil compaction, pollution, frost, salinity, competition (with weeds, exotic pasture, mistletoe, understorey shrubs etc.), exposure, nutrient deficiencies, or fire. Manion (1981) separated factors contributing to dieback into three categories – predisposing, inciting and contributing. Manion argued that least one agent from each category must be acting on a
system for dieback to occur. Predisposing factors act in the long term, creating the conditions required for dieback to occur and may include climate, soil or genetics. Inciting factors are short term disturbances or stresses such as drought or frost. Contributing factors are opportunistic organisms (viruses, fungi, insects etc.) that take advantage of the stressed state of the trees. Depending on the situation some factors may fall within more than one category. Insects may fall within all three categories; where regular outbreaks occur they may be classed as inciting or predisposing factors, however they are generally considered to be contributing factors taking advantage of the trees’ weakened state.

White (1969; 1984) suggested that stressed trees mobilise nutrients as they begin to senesce, improving the dietary quality of the foliage and thus increasing the insects’ survival and growth rates. Contrary to the traditional view of top-down population control by predators, White proposed that populations are limited by the availability and quality of their food, particularly in relation to the survival and growth of the young (White, 2003). An increasing number of studies have found evidence for this, with nitrogen content being the most important factor (Slansky & Feeny, 1977; Lightfoot & Whitford, 1987; Webb & Moran, 1978; White, 2008). A study of the chrysomelid beetle *Paropsis atomaria*, which feeds on several species of eucalypts, found that larval growth rates in the lab were positively correlated with foliar nitrogen levels (Fox & Macauley, 1977). When nitrogen levels in *Acacia karroo* plants were manipulated in the field, the population of a native psyllid (*Acizzia russellae*) increased ten-fold, and no evidence was found that natural enemies contributed to population control (Webb & Moran, 1978). A number of field studies have found that trees suffering from dieback have higher foliar nutrient levels than neighbouring trees, as well as greater insect numbers and defoliation rates (Marsh & Adams, 1995; Landsberg & Wylie, 1983; Granger, et al., 1994).

Water stress in particular has been suggested as the primary cause of many dieback episodes (Allen, et al., 2010; Auclair, 1993; White, 1969; Pook & Forrester, 1984). Several laboratory and field experiments have shown that water stressed trees have higher foliar nitrogen levels (Marsh & Adams, 1995; Miles, et al., 1982; Huberty & Denno, 2004). White (1969; 1986) found that psyllid outbreaks across Australia were correlated with large seasonal fluctuations in rainfall, and hypothesised that the insects were responding to increased nitrogen levels in senescing foliage. Despite this relationship, several studies have found that other effects of water stress such as wilting and reduced growth appear to counteract the benefit to insects provided by the increase in nitrogen levels (Huberty &
During a severe drought in 1982, Landsberg (1985) measured levels of water stress at several sites affected by dieback, and found that there was no relationship between water stress and the level of dieback measured before or after the drought. White (2009) later suggested that only senescence feeders may be able to benefit from plant stress, while flush feeders that require new growth are likely to benefit from vigorously growing plants (see next section on plant vigour).

Many rural landscapes have experienced a decline in the health of paddock trees as well as remnants of woodland on farms. Rural dieback is thought to be the result of tree stress, caused by a general simplification of the landscape which upsets the ecological balance. Contributing factors may include physical damage by machinery or stock, clearing leading to isolation and loss of habitat, nutrient imbalances caused by fertiliser application, competition with pastures and crops, and salinity (Figure 4) (Landsberg & Wylie, 1983; Landsberg & Wylie, 1988). A Tasmanian study found that tree decline was associated with exotic pastures, a lack of native vegetation and high nitrogen levels, and was strongly related to grazing pressure (Davidson, et al., 2007).

![Figure 4: A model of Euclaypt dieback as a result of land management practices. From Landsberg and Wylie (1988)](image-url)
Fire plays a very important role in eucalypt ecosystems, and the exclusion of fire can cause a range of changes that may place trees under stress such as promoting the development of a dense understorey, changed soil conditions and nutrient imbalances (Figure 5) (Close, et al., 2009; Jurskis & Turner, 2002; Jurskis, 2005b). In the absence of fire, fire intolerant understorey species proliferate and compete with the overstorey for water and inhibit eucalypt regeneration (Close, et al., 2011). In Ocean Grove, Victoria, a long unburnt grassy woodland showing signs of decline was surveyed in 1977 (Withers & Ashton, 1977) and revisited in 1998 (Lunt, 1998). In this time, the overstorey had continued to decline and the site had become dominated by Allocasuarina scrub, which suppressed eucalypt regeneration by creating a dense litter layer and shading seedlings. This change in composition was attributed to the absence of fire for over 100 years.

Fire is also very important for nutrient cycling. Long periods without fire can lead to imbalances as nitrogen builds up through fixation and atmospheric deposition while other nutrients become locked up in plant tissues and litter (Jurskis, et al., 2011; Turner & Lambert, 2005; Turner, et al., 2008; Close, et al., 2009; Close, et al., 2011). Dense understorey and increased litter can also create cooler and wetter soil conditions, inhibiting root growth and symbiotic mycorrhizal fungi (Ellis & Pennington, 1992; Bushfire CRC, 2011)

Figure 5: A model of Eucalypt dieback as a result of fire exclusion. From Jurskis and Turner (2002)
and increasing the risk of fungal infection (Marks, 1973). These changes may also encourage weeds and parasitic plants such as mistletoes that have been associated with dieback (Jurskis, et al., 2005). A low intensity fire can provide a pulse of water and nutrients to the overstorey and encourage regeneration (Close, et al., 2011b). In one Tasmanian study, *Eucalyptus delegatensis* affected by dieback recovered following felling and burning of the understorey (Ellis, et al., 1980).

It has been suggested that stressed trees may have reduced defence mechanisms and impaired ability to recover from defoliation, making them more susceptible to dieback (Landsberg & Wylie, 1988). Many plants produce chemicals such as tannins and oils that offer protection from phytophagous insects. While these compounds are effective at deterring insects that are not adapted to them, studies have shown that specialised species are unaffected by the concentration of toxic chemicals in the leaves (Morrow & and Fox, 1980; Fox & Macauley, 1977). Trees with physical damage such as cracks in the cambium are more easily invaded by fungi and bark boring insects; however this does not explain outbreaks of folivores. There is little evidence to support the idea that dieback occurs because stressed trees are unable to recover from defoliation, as trees affected by dieback produce prolific regrowth when protected from insect attack (Landsberg, et al., 1990).

Rather than being caused by increased nutrient availability in mature foliage, insects may respond to the production of epicormic growth after canopy loss due to fire or an acutely stressful event such as a heat wave. It is also possible that stressed trees simply have reduced growth, so that normal levels of insect damage cause a greater percentage loss of foliage; however this would also reduce the availability of new growth which is vital for flush feeders.

**Tree Vigour**

While there is strong evidence that nitrogen is a limiting factor for insects, there have been few studies to support the plant stress theory in the field. An alternative to this is the plant vigour theory proposed by Price (1991). Price suggested that insects are more likely to benefit from vigorous new growth on trees growing in benign conditions, in particular improved soil fertility. Several studies in the late 1980s and 1990s found that trees suffering from dieback on the southern tablelands of NSW had higher leaf and soil nitrogen levels than neighbouring healthy trees (Landsberg, 1990c; Landsberg, et al., 1990). This difference was attributed to input of nutrients from livestock camping under trees, fertilisation or pasture improvement.
It is now widely accepted that tree stress and tree vigour are not opposing or alternate theories but two ends of a spectrum (White, 2009). While insects that feed on mature or senescing tissues may benefit from trees under stress, specialist flush feeders may benefit from trees growing vigorously and producing large amounts of new foliage with high dietary quality (Price, et al., 1990; White, 2008; Schowalter, et al., 1999). Since most defoliating insects in Australia fall into the latter category, this theory is likely to apply to many cases of dieback (Landsberg & Cork, 1997).

2.2.4 Direct Climatic Effects
The coincidence of recent climate change with an increase in dieback episodes around the world suggests that the two may be related (Close & Davidson, 2004). Climate may have indirect effects on insect populations by altering ecological relationships with host plants or natural enemies. However, there may also be direct effects on insect survival, growth and phenology (Stange & Ayres, 2010).

Insect populations are highly responsive to changes in climate due to their short life span and huge reproductive potential. For most species, the increased temperatures predicted under climate change are expected to reduce mortality and increase growth rates. This combined with earlier emergence or reproduction could lead to additional generations in a year, and huge population increases as a result (Stange & Ayres, 2010). Other climatic factors may also have an effect, for example increased soil moisture may increase the survival of larvae or pupae in the soil (Heatwole & Lowman, 1986). For short-term factors to have an effect they must be well-timed to coincide with crucial stages of the insect life cycle.

2.3 Conceptual Diagram
The complicated nature of dieback is made more difficult by the fact that many of the contributing factors and mechanisms are interrelated. Figure 6 below illustrates this complexity by incorporating all the possible mechanisms leading to insect related dieback identified in the literature. At the bottom of the diagram is the feedback loop of repeated defoliation, with the five main mechanisms discussed above: missing or ineffective parasite or predator, isolation, tree stress, tree vigour and climatic factors. Each of these mechanisms may be caused by a range of factors. At the top are the initial disturbances such as climate change, fire exclusion and land management. Arrows indicate causal relationships working down through the diagram.
Figure 6: Dieback conceptual diagram
2.4 Where to from here?
Dieback is an extremely complex problem for which there is no simple answer. Although many theories have been put forward in the literature, none can explain why dieback occurs in each instance. Each episode is unique, with its own set of interrelated factors. In the next four chapters, I will investigate the Monaro dieback using a range of methods, to test whether any of the theories of dieback presented here could apply in this case. The hypotheses to be investigated, and methods used are summarised in Table 1 below.

<table>
<thead>
<tr>
<th>Hypothesis</th>
<th>Method</th>
<th>Chapter</th>
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<tbody>
<tr>
<td>The eucalyptus weevil is an exotic species</td>
<td>• Identify weevil</td>
<td>3</td>
</tr>
<tr>
<td>The weevil is the primary cause of dieback</td>
<td>• Literature search on diet and population dynamics</td>
<td>3</td>
</tr>
<tr>
<td>The weevil’s predator or parasite is missing</td>
<td>• Literature search to identify possible predators/parasites</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>• Measure parasitism rates</td>
<td>3</td>
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<td></td>
<td>• Structural Complexity Index</td>
<td>5</td>
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<td></td>
<td>• Analyse climate data</td>
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<tr>
<td>Dieback is caused by isolation</td>
<td>• Road survey</td>
<td>4</td>
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<td></td>
<td>• Paired site comparisons</td>
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<tr>
<td>Dieback is caused by tree stress</td>
<td>• Literature search on weevil diet and population dynamics</td>
<td>3</td>
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<td>• Road survey</td>
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<td>• White’s Climatic Stress Index and GROWEST Index</td>
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<tr>
<td>Dieback is caused by tree vigour</td>
<td>• Literature search on weevil diet and population dynamics</td>
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<td>• Paired site comparisons</td>
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<td>Dieback is caused by agricultural land use</td>
<td>• Road survey</td>
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<td>• Paired site comparisons</td>
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<tr>
<td>Dieback is caused by fire exclusion</td>
<td>• Paired site comparisons</td>
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<tr>
<td>Dieback is related to climate change</td>
<td>• Analyse climate data</td>
<td>6</td>
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</tbody>
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Chapter 3: The Eucalyptus Weevil

3.1 Introduction
While tree dieback may be caused by a range of interacting factors, it is often associated with insect attack. Although insect damage can be a primary cause of dieback, most often it is a secondary or contributing factor that occurs as a result of other underlying issues such as tree stress, nutrient imbalances, or climate (Manion, 1981). Certain aspects of insect life history including habitat, diet, oviposition site preference and population dynamics determine the likelihood that a species will cause a serious infestation under certain conditions, and for this reason understanding the life history of the insects involved in dieback may provide clues as to whether they are a primary or secondary factor, and what the underlying issues might be.

An initial study by Neil Murdoch into the cause of the Monaro dieback identified a weevil that appeared to be associated with the dieback. The weevil was found in large numbers on affected trees and causes characteristic damage to the leaves. Dieback was found to be most severe in *Eucalyptus viminalis*, which is the weevil’s preferred host species. Murdoch conducted a trial using stem-injected pesticides, and found that treated trees were prevented from declining further and began to show signs of recovery (Appendix 1). This evidence suggests that the weevil is the ultimate cause of death, but it is unclear whether they are the sole cause or the result of an underlying factor. This chapter looks at the traits of the weevil and the implications in diagnosing the Monaro dieback.

3.2 Identification of the Weevil
The weevil associated with the Monaro dieback was identified by Murdoch as the eucalyptus weevil (*Gonipterus scutellatus*), native to eastern Australia from southern Queensland through to Tasmania and South Australia (Elliott, et al., 1998). Although this identification is essentially correct, the species has recently been found to be a complex of ten genetically distinct but visually identical (cryptic) species, with restricted ranges (Mapondera, et al., 2012). It was therefore possible that the weevils causing the damage had been introduced from another part of Australia.

To identify the defoliating insect I collected live insect specimens from affected trees at a property near Dalgety (see Chapter 5, Figure 13, site 4). These specimens were identified by Dr. Oberprieler at the CSIRO Australian National Insect Collection. The specimens were found to be from an undescribed species known as *Gonipterus sp. no. 2*. This species was previously collected from sites in eastern NSW, Victoria and South Australia (Oberprieler...
pers. comm.). Interestingly, while the species is native to the Monaro region, it has been introduced to overseas eucalyptus plantations and become a serious pest in South Africa and parts of Europe (Tooke, 1953; Rivera, et al., 1999; Hanks, et al., 2000).

3.3 Description, Diet and Life History
Eucalyptus weevils are small, grey-brown beetles around 1 cm long with females slightly larger than males (Figure 7). They feed on a range of host species including *Eucalyptus globulus*, *E. smithii*, *E. delegatensis*, and especially *E. viminalis*. The latter is the weevil’s preferred host (Elliott, et al., 1998; Newete, et al., 2011). Both adults and larvae eat eucalypt foliage causing characteristic damage. That is- adults chew leaf edges creating a scalloped edge, while the larvae strip the epidermis of the leaf leaving trails of exposed tissue which goes dry and brown (Figures 7 and 8). Adult foliage and particularly new (adult) shoots are preferred over juvenile foliage (Matsuki & Tovar, 2010).

Eggs are laid on the new foliage in early spring, and hatch after 2-3 weeks. The larvae are slug-like and bright green with black spots, often with a long strand of excrement attached to the body (Figure 7). After 1-2 months the larvae drop to the ground and pupate in the soil before emerging as adults. There can be up to three overlapping generations in a year, with all stages usually present at once (Phillips, 1992). In colder areas, adults emerging late in autumn hibernate over winter under bark or clinging to branches and delay egg laying until the following spring, while the pupae remain underground until sufficient rain occurs in spring. Above a certain temperature threshold this hibernation does not occur and adults continue feeding and ovipositing throughout the winter (Tooke, 1953).

![Figure 7: The eucalyptus weevil - adult, larva and egg case. Some damage to leaf epidermis caused by larval feeding also visible. Photo: Catherine Ross](image)

*Figure 7: The eucalyptus weevil - adult, larva and egg case. Some damage to leaf epidermis caused by larval feeding also visible. Photo: Catherine Ross*
3.4 Population Dynamics
As described in Chapter 2, phytophagous insects can be classified according to their diet (bark borers, sap suckers etc., flush or senescence feeders), and population dynamics (eruptive or latent). These classifications provide clues about the underlying causes of dieback.

Eucalyptus weevils are leaf chewers, and feed preferentially on new flushing foliage (Matsuki & Tovar, 2010; personal observation). They also require new growth for egg laying sites, resulting in strong competition between females for suitable sites. This intraspecies competition, along with food availability and quality, and parasitism, plays a large role in limiting population (Price, et al., 1990). Typically, this species occurs at steady, low population levels, and can therefore be classified as a latent species (Landsberg & Cork, 1997). Unlike an eruptive species with cyclic patterns of outbreak, latent species require a release of one or more limiting factors in order to have a population outbreak. It is therefore likely that in the case of the Monaro dieback the insect attack is not the primary cause but a secondary factor resulting from underlying issues.

Due to the weevils’ requirement for new foliage for feeding and oviposition sites, it is expected that they would benefit from conditions that increase the availability or quality (nutritive value) of new foliage, as described by the tree vigour hypothesis.

3.5 Predators and Parasites
Eucalyptus weevils have a number of natural enemies, including several species of egg-parasitoid wasp in the genus *Anaphes*, and several species of wasps and flies that parasitise
the larvae (Elliott, et al., 1998; Phillips, 1992; Tooke, 1953; Huber & Prinsloo, 1990). Predators of the eucalyptus weevil may include insectivorous birds and other predatory insects and spiders.

Where Gonipterus species have become pests in overseas eucalyptus plantations, biological control using the parasitoid wasp Anaphes nitens has in many cases been very successful. A. nitens was discovered in the 1920s and introduced to South Africa (Tooke, 1953). Several studies have found that the parasitoid is less effective at high elevation, low temperatures, and under adverse climatic conditions such as drought (Reis, et al., 2012; Tooke, 1953). The wasp’s development is completely dependent on the presence of weevil eggs and the adults do not live long, so when the weevils go into winter hibernation the wasp population can collapse and take several weeks to recover enough numbers to effectively control the weevil. Weevil egg numbers may also be reduced under drought conditions when oviposition sites on new flushing foliage are scarce (Loch, 2006).

There is a very specific relationship between A. nitens and its host. The failure of biological control using A. nitens in Western Australia (Loch, 2008) prompted further research by Mapondera and colleagues into the relationship between parasite and host, and found that “only the undescribed species in Africa, Italy and France (sp. no. 2) is a natural host for the egg parasitoid Anaphes nitens, which is used to control all of them.” The pest species in Western Australia is now recognised as Gonipterus platensis, a native of Tasmania where A. nitens does not occur (Mapondera, et al., 2012).

3.5.1 Study: Estimating parasitism rates on the Monaro
The success of biological control using Anaphes nitens suggests that parasitism plays a large role in controlling weevil populations in their natural habitat. If parasitism rates on the Monaro are low, this may explain the outbreak. In order to estimate parasitism rates, I collected egg masses from the field and attempted to raise them to hatching and count the numbers of weevils and wasps that emerged. Unfortunately, the experiment was unsuccessful as the egg masses failed to develop. The reason for this was unclear and time constraints prevented the experiment being repeated.

3.6 Conclusions
The weevil found to be involved with the Monaro dieback is a previously undescribed species known as Gonipterus sp. no. 2, part of a complex of ten cryptic species previously known as Gonipterus scutellatus. This weevil is native to the region but has become a serious pest when introduced overseas.
The eucalyptus weevil is a specialist flush feeder, preferring new flushing foliage for both adults and larvae, and for oviposition sites. Competition for limited resources, along with parasitism and predation, maintain low population levels typical of latent species. Outbreaks of this type of insect may be triggered by conditions that increase the availability or quality of new foliage, or decrease predation or parasitism rates. These possible explanations will be explored in the following chapters.
Chapter 4: Road Survey

4.1 Introduction

Spatial information relating to the extent, severity and patterns of dieback are vital for diagnosis of the problem, and for understanding the relationships between dieback and other factors such as climate or land use. Prior to this study, no such information was available for the Monaro dieback apart from casual or localised observations by landholders and people travelling through the area. To address this lack of information, a road survey was conducted with an aim to cover the affected area and record photographic and observational data systematically along the route.

In 1986, (Mackay, et al.) a road survey was conducted in the New England region of NSW, which was severely affected by rural dieback. They found that dieback was most severe on grazing country, especially areas that had been partially cleared, and that neighbouring forested areas were unaffected. These findings supported the theory that the underlying cause of rural dieback may be related to agricultural practices (see Chapter 2). Many aspects of the Monaro dieback are similar to New England – they are both high elevation tablelands areas that have been partially cleared and are used mainly for grazing. If the Monaro dieback is a form of rural dieback, one would expect that grazed, improved and/or partially cleared areas would be affected, while nearby ungrazed reserves or forests remain intact. Another similar episode in the midlands of Tasmania was found to be related to the position in the landscape. Trees growing in gullies or depressions were found to be healthier than those in exposed or well-drained conditions, indicating that drought may play a role (Doyle, 2005).

Remote sensing may allow mapping of dieback on a large scale, and has been shown to have the potential to detect changes in leaf pigmentation caused by insect damage (Stone, et al., 2001). However, remote sensing is limited by the availability of imagery and the difficulty in differentiating between eucalypt species and between trees affected by insect attack and other causes of defoliation such as fire, ringbarking or fungal disease. In addition, other information such as the presence or absence of the weevil itself can only be obtained with on-ground observation.
4.2 Methods

The survey covered main roads and some secondary roads across the affected area, stopping at 5 km intervals along the route. In any direction, I travelled 10-15 km beyond the edge of the affected area (where affected trees were no longer evident) before stopping or turning around. At each stop, two photographs were taken to the left and right of the road, using a camera with GPS capability. Additional photos were taken at any point along the route to record interesting observations.

At each stop I also recorded the overstorey species present, the severity of dieback on a scale from 1 to 5 (Figure 9), the apparent land use (grazing, cropping, residential/garden, public or private reserve, plantation), vegetation type (forest, woodland, paddock), presence or absence of a shrubby understorey, and the position in the landscape (hill top, slope, flat). Observations were recorded as far as was visible in any direction (up to approx. 2 km).

At some stops where trees were easily accessible, I looked for evidence of the presence of weevils; either adults, larvae, eggs or feeding damage.

The photographs and data were then mapped in Google Earth using the GPS data, in order to visualise spatial patterns and show the extent of the problem.

Figure 9: Stages of tree dieback. (5) Healthy tree, (4) canopy thinning from edges, (3) epicormic growth, (2) extensive dead branches and epicormic growth, (1) tree death. Scores of 5 or 4 are classified as healthy (although 4 may indicate early stages of dieback these symptoms are common amongst eucalypts and scores of 5 are very rare), 3 - 1 are classified as dieback. Adapted from Heatwole and Lowman (1986).
4.3 Results
The road survey covered around 400 km of main roads in the Monaro region between Bredbo, Numeralla, Nimmitabel and Jindabyne, with 75 stops at 5 km intervals (Figure 10, Appendix 3). At 34 of those stops (45%) *Eucalyptus viminalis* were present, with 26 of those (76%) showing clear signs of dieback (Appendix 3).

4.3.1 Extent
The Monaro dieback covers a total geographical area of around 2000 km² (Figure 10). The edges of the affected area appear to be gradual, and seem to be defined by changes in species composition from communities dominated by the susceptible *E. viminalis* to other communities.

![Figure 10: Map of the Monaro region. Blue lines show route of road survey, which covered around 400km. The light red area indicates the dieback affected area, around 2000 km², and the central darker red indicates the worst affected area (crown scores 1-2). This area is approximate, based on observations made at 75 stops along the survey route at 5 km intervals. An interactive version of this map is provided on the attached DVD (Appendix 4).](image-url)
Dieback extends north along the Monaro Highway as far as Bredbo where the *E. viminalis*/*E. rubida*/*E. pauciflora* community is replaced by Box-Gum Woodland dominated by *E. melliodora*/*E. bridgesiana*/*E. blakelyi*. To the east evidence of dieback can be seen on the Numeralla Rd until a few kilometres west of Numeralla where there is a change to *E. rossii*/*E. macrorhyncha* dry sclerophyll forest. A few relatively healthy *E. viminalis* were found east of Numeralla along the Countegany Rd. To the west the species composition changes to be dominated by *E. pauciflora* at the top of Barney’s range, but dieback is still evident in scattered *E. viminalis* until they disappear around 10 km before Jindabyne. The southern boundary occurs around Nimmitabel, and is the only boundary which is defined by a change from affected to healthy *E. viminalis* rather than a species change.

Within this region, every *E. viminalis* observed was affected by dieback, with clear evidence of insect attack, dead branches, and epicormic growth. Areas that were free of dieback, in particular forested hill tops (such as Wullwye State Forest, located between Berridale and Dalgety), were again due to changes in species rather than a change from affected to healthy *E. viminalis*.

### 4.3.2 Severity

*E. viminalis* were the most affected species, with *E. rubida* affected to a lesser extent. Other eucalypt species such as *E. pauciflora*, *E. stellulata* and *E. bridgesiana* did not appear to be affected, although some showed evidence of insect attack especially on the outer edges of the crown. Other native genera such as *Acacia*, and exotic genera such as *Salix*, *Populus* and *Pinus* appeared to be unaffected.

A range of dieback severity was recorded within *E. viminalis* stands. There was little variation in severity amongst individuals at each stop; however some locations were more badly affected than others. The most severely affected area was between Cooma and Berridale, where most *E. viminalis* were dead or very near to death (score 1-2) (Figure 10). Trees on the periphery of the dieback appeared to be less affected, for example those on Barney’s Range, on the lower slopes of Wullwye Nature Reserve, and around Bredbo and Numeralla. Some areas around Cooma also seemed to be less affected, for example there appears to be a gradual decline in tree health when heading out of Cooma on the Snowy Mountains Highway.

### 4.3.3 Spatial Patterns

On the Monaro, *E. viminalis* tend to occur in patches of woodland on low rocky outcrops or ridges and the lower slopes of larger hills. The larger hill tops are generally dominated by
dry or wet sclerophyll forest, and the flats are natural or derived grassland (where the canopy has been cleared). As a result, most sites with *E. viminalis* were woodlands with a sparse to dense understorey present. Most sites had evidence of grazing by sheep or cattle (animals, dung, tracks or herbivory present), but few were heavily grazed.

![Figure 11: Dieback between Cooma and Berridale. To the left of the fence is a TSR, to the right a frequently grazed private property. There is no difference in the severity of dieback between these different land uses. Photo: Catherine Ross](image)

There were no obvious spatial patterns or relationships with land use, vegetation type, presence of understorey, or position in the landscape (Appendix 3). Reserves were equally as affected as neighbouring grazing land. Scattered travelling stock reserves (TSRs) were the most obvious example of affected reserves. These areas were relatively undisturbed and are grazed by cattle or sheep infrequently if at all. Some had a healthy and diverse native understorey. There was no difference in the severity of dieback between TSRs and neighbouring properties that had obvious evidence of grazing (Figure 11). Trees in river valleys were also equally affected (Figure 12).

![Figure 12: Trees in a river valley near Berridale are still severely affected by dieback. Photo: Catherine Ross](image)

**4.3.4 Other Observations**

Although aspect was not recorded at each stop on the road survey, observations made while driving the route did not show any obvious relationship between aspect and severity of dieback. Variation in severity tended to be on a larger scale of tens of kilometres rather than within small patches of trees. Very little mistletoe was observed through the whole region, and there was no evidence of fungal infection (cankers, bleeding, leaf browning,
affects a wide range of species) or salinity. Two areas showed evidence of burning – the southern slope of Barney’s Range (Avonside Rd) and parts of Bobundara Nature Reserve (Maffra Rd).

At one location on Dalgety Rd between Berridale and Dalgety, a single *E. viminalis* growing in an apparently well watered garden was healthier than the surrounding trees. This was the only example I found of an obvious difference in health between neighbouring trees.

Weevils were found to be present on all *E. viminalis* sampled on the road survey, including adults, larvae, eggs and characteristic leaf damage. (Weevils were also found on healthy *E. viminalis* opportunistically sampled in other areas around south-eastern NSW including Canberra, Sutton, and Bungendore.) Adult and larval feeding damage was obvious on all affected trees, and the weevils were easily found on leaves or clinging to stems. Eggs and larvae were usually found on newly expanding adult and epicormic growth, sometimes in large numbers. No weevils were found on other co-existing eucalypt species, however a range of other insects and insect damage were observed on all eucalypt species.

### 4.4 Discussion

The Monaro dieback was found to cover a huge area, almost the size of the ACT. The size of the problem should cause concern, as this area is now almost entirely devoid of living trees apart from isolated hill tops and scattered exotics such as poplar, willow and pine. This represents a huge loss in terms of production, biodiversity and aesthetics. The road survey was able to give a good idea of the extent, severity and spatial patterns of dieback, and provide hints towards possible causes.

Anecdotally, there have been reports of clear boundaries where dieback suddenly stops (Freudenberger pers.comm.). From observations made on the road survey, these boundaries appear to be caused by a change in species composition, to communities that are no longer dominated by the susceptible *E. viminalis*. The few sites containing healthy *E. viminalis* were on the edges of the affected area and in most cases showed signs of dieback in the early stages (trees with scores of 4 were not classified as dieback but displayed some signs of insect damage and dead twigs at the edge of the crown which may be early symptoms of dieback). The change in plant communities is likely to be caused by a range of factors including climate and soil type.

The severity of the dieback observed seemed to be related to the length of time that dieback had been observed at that site, based on anecdotal evidence collected either at the
Greening Australia field day in 2011 (Appendix 2), or from landholders and researchers spoken to during the project. For example, dieback had been noticed in the worst affected area between Berridale and Cooma for 5-10 years (Murdoch pers. comm.); while landholders on Barney’s Range (between Berridale and Jindabyne) (O’Brien pers. comm.) and the southern side of Wullwye Nature Reserve (north of Dalgety) (Rudd pers. comm.) first noticed dieback within the last 1-2 years. These areas are on the periphery of the affected area, suggesting that the dieback may have spread from a central starting point. From speaking with local landholders, Neil Murdoch believed that the starting point was a TSR just outside Berridale (Murdoch pers. comm.); however this anecdotal information is very difficult to confirm. The possibility that the dieback is spreading is concerning, given the proximity of Kosciuszko National Park.

In previous studies of rural dieback, healthy trees were often found neighbouring those affected by dieback. This allowed a clear comparison between healthy and declining trees within a small area, eliminating many of the potential explanations for the dieback. In this case, all susceptible trees within the range of a few kilometres appeared to be affected almost equally, and almost no healthy trees were found within the boundary of the affected area. The uniformity of severity within sites may be due to the extended period that the area has been affected – perhaps when the dieback started there was a difference between neighbouring trees, but over time the insects may have moved to less preferred foliage. Alternately it may indicate that the cause of the dieback is on a larger scale and may reflect a landscape-scale change.

4.5 Conclusions
The Monaro dieback covers an area around 2000km², with edges largely defined by a change in species composition. The most severe dieback occurs in the centre of the affected area while the edges are less affected. This relationship indicates that the dieback may have spread from a central location to its current extent.

No relationship was found between the severity of dieback and land use, presence of understorey, aspect or position in landscape, and there was little variation between individual trees within sites. The lack of any obvious spatial patterns related to land use or the presence of an understorey suggests that these factors do not play a role in the dieback. These aspects of management will be investigated further in the next chapter.
Chapter 5: Structural Complexity – Paired Site Comparisons

5.1 Introduction
The Monaro dieback shows many similarities with dieback occurring on the New England tablelands. Known as rural dieback, it typically occurs on grazing land that has been partially cleared, with little or no native understorey or woody debris to provide habitat for insect predators, and a history of fertilisation or pasture improvement which increases the nutrient content of the soil and foliage (Mackay, et al., 1984). These landscapes are structurally simplified, and management actions usually involve improving structural complexity with the assumption that this will increase the resilience of these landscapes to decline.

On the other hand, the fire exclusion theory of dieback suggests that the same attributes that indicate a structurally diverse and resilient landscape are actually contributing to dieback and are symptoms of fire exclusion from areas that would once have experienced frequent, low intensity fires (Jurskis, 2005b; Close, et al., 2009). A dense understorey and deep leaf litter indicate a change in nutrient cycling that places stress on trees and increases the dietary quality of the foliage (Jurskis & Turner, 2002).

The road survey (see chapter 4) found that the Monaro dieback affects all *E. viminalis* within boundaries defined by a change in species composition. Pairs of sites were chosen from within the affected area, which differed in land management, fire history or structural attributes. At each site the dieback severity was measured as well as a range of structural attributes to give an indication of the relationship between structural complexity, land management, fire regime and dieback.

5.2 Methods

5.2.1 Site Selection and Description
Eight sites were selected for study from the affected area (Figure 13), with a range of management and fire histories, dieback severity and structural attributes (summarised in Table 2). The sites were chosen based on several aspects: presence of *E. viminalis*, management history, and ease of access (physical ease and communication with landholder). Two sites were travelling stock reserves (TSRs) near Berridale and Dalgety, in the worst affected area. Anecdotal evidence suggests that the Berridale TSR was one of the first locations where dieback was observed (Murdoch pers. comm.). These sites were relatively undisturbed, with no evidence of heavy grazing, pasture improvement or
Table 2: Site descriptions of eight paired sites selected from around the Monaro region.

*Dieback noticed in last two years.
^Sites burnt in 2003
Site 4 landowner pulled out so detailed measurements could not be taken.

<table>
<thead>
<tr>
<th>Site number</th>
<th>1</th>
<th>2</th>
<th>3*</th>
<th>4</th>
<th>5*^</th>
<th>6*^</th>
<th>7*^</th>
<th>8*^</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site name</td>
<td>TSR Berridale</td>
<td>TSR Dutton</td>
<td>Rudd</td>
<td>Sunnyside</td>
<td>O’Brien1</td>
<td>O’Brien2</td>
<td>Dickson1</td>
<td>Dickson2</td>
</tr>
<tr>
<td>Grazed/ungrazed</td>
<td>Ungrazed</td>
<td>Ungrazed</td>
<td>Grazed</td>
<td>Grazed</td>
<td>Ungrazed</td>
<td>Ungrazed</td>
<td>Ungrazed</td>
<td>Ungrazed</td>
</tr>
<tr>
<td>Burnt/unburnt</td>
<td>Unburnt</td>
<td>Unburnt</td>
<td>Unburnt</td>
<td>Unburnt</td>
<td>Unburnt</td>
<td>Unburnt</td>
<td>Burnt</td>
<td>Burnt</td>
</tr>
<tr>
<td>Forest/woodland/paddock</td>
<td>Woodland</td>
<td>Woodland</td>
<td>Woodland</td>
<td>Woodland</td>
<td>Forest</td>
<td>Forest</td>
<td>Forest</td>
<td>Paddock</td>
</tr>
<tr>
<td>Improved/not improved</td>
<td>Not improved</td>
<td>Not improved</td>
<td>Not improved</td>
<td>Not improved</td>
<td>Improved</td>
<td>Not improved</td>
<td>Not improved</td>
<td>Improved</td>
</tr>
<tr>
<td>Elevation (approx.)</td>
<td>900m</td>
<td>900m</td>
<td>900m</td>
<td>900m</td>
<td>850m</td>
<td>850m</td>
<td>1000m</td>
<td>1000m</td>
</tr>
<tr>
<td>Aspect</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>SE</td>
<td>S</td>
</tr>
<tr>
<td>Mean annual rainfall (mm)</td>
<td>536</td>
<td>536</td>
<td>593</td>
<td>536</td>
<td>567</td>
<td>567</td>
<td>567</td>
<td>567</td>
</tr>
<tr>
<td>Mean annual temperature (°C)</td>
<td>11.3</td>
<td>11.2</td>
<td>10.4</td>
<td>11.2</td>
<td>11.2</td>
<td>11.2</td>
<td>11.2</td>
<td>11.2</td>
</tr>
<tr>
<td>Dominant overstorey species</td>
<td>E. viminalis</td>
<td>E. viminalis</td>
<td>E. viminalis</td>
<td>E. viminalis</td>
<td>E. viminalis</td>
<td>E. viminalis</td>
<td>E. viminalis</td>
<td>E. viminalis/E. pauciflora</td>
</tr>
</tbody>
</table>

Figure 13: Eight sites selected from the dieback affected region – site descriptions in Table 2.
burning. These were paired with a private property on the southern boundary of Wullwye State Forest, a forested hill to the east of Dalgety. This site was used regularly for sheep grazing but had not been pasture improved or burnt. A second grazed site was chosen on a private property neighbouring site 2, however the landowner subsequently refused access (for unknown reasons) so detailed measurements could not be taken but simple observations were made. The last four sites were located on two neighbouring properties on Barney’s Range, on the western edge of the affected area. One property was partially burnt in 2003, providing an excellent comparison between adjacent burnt and unburnt areas. At the other property (which was also burnt in 2003), one site provided an example of a forested area less dominated by *E. viminalis*; the other was a clearing in the forest with a history of cropping and fertilisation but not for at least six years.

5.2.2 Detailed Measurements
At each site, a range of structural attributes were measured as per the McElhinny Structural Complexity Index (SCI), and an estimate of dieback severity was taken for a sample of trees.

**McElhinny Structural Complexity Index**
The SCI measures several structural attributes of a forest or woodland and compares these against other equivalent sites to give an overall score for the site. Higher scores indicate a higher structural complexity, and generally indicate sites that are relatively undisturbed or have old-growth characteristics (McElhinny, et al., 2006).

In addition to the overall SCI score, each attribute is given a poor, average or high rating with accompanying recommendations for management. Each of the thirteen attributes (listed below) has been shown to be significantly correlated with species diversity and abundance. The attributes measured are chosen because they are easy to measure, are useful for differentiating sites, and can be used as surrogates for other attributes (McElhinny, et al., 2006). The methods for measuring each attribute are taken from McElhinny et al. (2006)(Appendix 5).

The thirteen attributes are:

- the number of perennial species
- number of lifeforms
- basal area of live trees
- quadratic mean DBH
- percentage vegetation cover <0.5m
- percentage vegetation cover 0.5-6m
• overstorey regeneration
• hollow bearing trees
• trees with DBH >40cm
• dead trees
• total length of logs diameter >10cm
• total length of logs diameter >30cm
• litter dry weight

Each attribute is compared with the expected levels for a particular community, based on a set of reference sites. It is important to note that the Index can only be applied to communities that are similar in structure to those used to develop the Index. If a different community is being assessed, a new set of reference sites would need to be established.

The SCI was originally developed for dry sclerophyll forest and grassy woodland communities in the region just to the north of Canberra (Gunning, Binalong, Frogmore area), where annual rainfall ranges between 400 and 800mm (McElhinny, et al., 2006). It was decided that although the Monaro region is outside this area, the vegetation communities and climate are sufficiently similar for the original reference sites to be used.

To calculate the SCI the site is compared against either woodland or forest reference sites, to account for innate structural differences between these vegetation types. For example even high quality forest would not be expected to have as high a level of ground cover as woodland. For the analysis, sites 1, 2, 3, 4 and 8 were classified as woodland, while sites 5, 6 and 7 were considered to be forest based on estimates of canopy cover (in this case potential canopy cover, as much of the canopy had been removed through defoliation).

At site 4 where measurements could not be taken, each attribute was given a poor, average or good rating based on visual estimation. As this can only give a rough estimate of the Structural Complexity Index, this site was not included in the analysis but was useful as observational data.

Estimating Dieback- Crown Condition Score

The method described in Stone, et al. (2008)(see Appendix 6) was used to estimate the severity of dieback for each tree within the plots established for the SCI. This method was chosen because it is simple to measure, and has been shown to have high accuracy and low observer bias (Horton, et al., 2011).

Each tree is given a score out of five for five parameters of tree health - crown size and shape, foliar density, dead branches, epicormic growth, and foliar damage. The crown
condition score is the sum of these five parameters, giving a total score out of 25. High scores represent very healthy, vigorous trees. A score of zero represents a tree that is completely dead, with no living foliage remaining.

5.3 Results

The SCI scores ranged from 54 to 64 (33.3 to 76.5 percentile) when compared with appropriate reference sites (woodland or forest) (see Table 3). Scores for all attributes were quite variable across sites. Most sites scored poorly in some attributes but highly in others. Some sites scored well outside the reference range in certain attributes.

Table 3 shows the results for each attribute as well as the overall SCI score and percentile ranking. The colours indicate whether the site was poor, average, good or very high (outside the reference range) for that attribute, as compared to the reference sites.

All eight sites were affected by dieback, with overall crown scores ranging from 4.76 to 17.04 (out of a maximum of 25) (Table 4). The lowest scoring sites were the TSRs, followed by the Rudd (site 3) and O’Brien sites (sites 5 and 6), and finally the Dickson sites (sites 7 and 8). The species specificity of the dieback was confirmed, with *E. viminalis* the worst affected on average across all sites, followed by the closely related *E. rubida* (Figure 14, 15). Other overstorey species were not affected, e.g. *E. pauciflora*. Juvenile trees were less affected than adult trees across all sites, but there was no difference between dominant or co-dominant trees and suppressed trees (Figure 16). To account for sites with greater numbers of juveniles or less affected species, the crown score was also calculated for adult *E. viminalis* only. This reduced the score for all sites, but the greatest difference was at site 7 which dropped from a score of 17.04 to 7.61.

There was a very weak positive correlation between the crown scores (adult *E. viminalis* only) and overall SCI for each site (Pearson’s correlation coefficient ($r$) = 0.3, non-significant). However there was a significant positive correlation between the crown scores and basal area ($r = 0.95$, $p <0.05$), and quadratic mean diameter ($r = 0.07$, $p <0.05$), and a significant negative correlation between crown health and the number of dead trees ($r = -0.7$, $p <0.05$).
Table 3: Measurements taken from eight paired sites selected from within the dieback affected area (for site descriptions see Table 2). Thirteen structural attributes contribute to the Structural Complexity Index score. For raw data see Appendix 4. *Site 4 scores are estimations based on ocular measurements and photographs.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4*</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of perennial species (species/400m^2 plot)</td>
<td>13.5</td>
<td>13.67</td>
<td>9.67</td>
<td>16.33</td>
<td>19.67</td>
<td>23.33</td>
<td>10.33</td>
<td></td>
</tr>
<tr>
<td>Number of lifeforms (lifeforms/400m^2 plot)</td>
<td>5.5</td>
<td>5.66</td>
<td>6</td>
<td>8.3</td>
<td>9</td>
<td>7.67</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Basal Area of live trees (m^2/ha)</td>
<td>1.49</td>
<td>0.09</td>
<td>8.99</td>
<td>13.88</td>
<td>7.44</td>
<td>6.67</td>
<td>18.72</td>
<td></td>
</tr>
<tr>
<td>Quadratic mean dbh (cm)</td>
<td>22.28</td>
<td>5.76</td>
<td>22.14</td>
<td>30.21</td>
<td>21.58</td>
<td>11.53</td>
<td>36.95</td>
<td></td>
</tr>
<tr>
<td>0-0.5m veg cover (%)</td>
<td>88.75</td>
<td>96.7</td>
<td>68.33</td>
<td>70</td>
<td>75.56</td>
<td>72.92</td>
<td>91.25</td>
<td></td>
</tr>
<tr>
<td>0.5-6.0m veg cover (%)</td>
<td>8.44</td>
<td>13.70</td>
<td>13.42</td>
<td>24.17</td>
<td>60.69</td>
<td>20.00</td>
<td>5.83</td>
<td></td>
</tr>
<tr>
<td>Overstorey regeneration (stems/ha)</td>
<td>10</td>
<td>26.6</td>
<td>40</td>
<td>36.67</td>
<td>60</td>
<td>613.33</td>
<td>290</td>
<td></td>
</tr>
<tr>
<td>Hollow bearing trees (stems/ha)</td>
<td>5</td>
<td>26.6</td>
<td>6.67</td>
<td>30</td>
<td>60</td>
<td>3.33</td>
<td>13.33</td>
<td></td>
</tr>
<tr>
<td>Trees with dbh&gt;40(stems/ha)</td>
<td>32.5</td>
<td>36</td>
<td>23.33</td>
<td>56.67</td>
<td>26.67</td>
<td>20</td>
<td>26.67</td>
<td></td>
</tr>
<tr>
<td>Dead trees (stems/ha)</td>
<td>72.5</td>
<td>43.3</td>
<td>26.67</td>
<td>16.67</td>
<td>50</td>
<td>50</td>
<td>33.33</td>
<td></td>
</tr>
<tr>
<td>Length of logs (&gt;10cm diameter) (m/ha)</td>
<td>405</td>
<td>410</td>
<td>1014</td>
<td>4908</td>
<td>4275</td>
<td>731.33</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Length of large (&gt;30cm diameter) logs (m/ha)</td>
<td>311.25</td>
<td>128</td>
<td>203.5</td>
<td>3600</td>
<td>1158</td>
<td>103.33</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Litter dry weight (t/ha)</td>
<td>0.43</td>
<td>0.5</td>
<td>0.46</td>
<td>1.79</td>
<td>2.87</td>
<td>1</td>
<td>0.44</td>
<td></td>
</tr>
<tr>
<td>Structural Complexity Index score</td>
<td>61</td>
<td>64</td>
<td>62</td>
<td>61*</td>
<td>61</td>
<td>62</td>
<td>54</td>
<td>64</td>
</tr>
<tr>
<td>Percentile ranking</td>
<td>70.6</td>
<td>76.5</td>
<td>76.5</td>
<td>70.6*</td>
<td>48.5</td>
<td>54.5</td>
<td>33.3</td>
<td>76.5</td>
</tr>
</tbody>
</table>

Table 4: Five attributes contribute to the dieback score, calculated for all trees and for adult E. viminalis only. For raw data see Appendix 4.

<table>
<thead>
<tr>
<th>Dieback</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown size/shape (/5)</td>
<td>0.93</td>
<td>1.38</td>
<td>2.21</td>
<td>2.33</td>
<td>1.86</td>
<td>3.44</td>
<td>2.75</td>
<td></td>
</tr>
<tr>
<td>Foliar density (/5)</td>
<td>0.98</td>
<td>1.43</td>
<td>2.08</td>
<td>2.35</td>
<td>1.79</td>
<td>3.41</td>
<td>2.65</td>
<td></td>
</tr>
<tr>
<td>Dead branches (/5)</td>
<td>0.86</td>
<td>1.48</td>
<td>2.19</td>
<td>2.22</td>
<td>1.66</td>
<td>3.32</td>
<td>2.76</td>
<td></td>
</tr>
<tr>
<td>Epicormic growth (/5)</td>
<td>1.12</td>
<td>1.71</td>
<td>1.87</td>
<td>2.50</td>
<td>2.07</td>
<td>4.02</td>
<td>4.12</td>
<td></td>
</tr>
<tr>
<td>Foliar damage (/5)</td>
<td>0.88</td>
<td>1.19</td>
<td>2.00</td>
<td>2.08</td>
<td>1.64</td>
<td>2.86</td>
<td>2.51</td>
<td></td>
</tr>
<tr>
<td>Total (all trees)</td>
<td>4.76</td>
<td>7.19</td>
<td>10.35</td>
<td>4*</td>
<td>11.48</td>
<td>9.01</td>
<td>17.04</td>
<td>14.79</td>
</tr>
<tr>
<td>Total (adult vims only)</td>
<td>0.72</td>
<td>1.15</td>
<td>8.65</td>
<td>1*</td>
<td>9.87</td>
<td>6.55</td>
<td>7.61</td>
<td>12.75</td>
</tr>
</tbody>
</table>
Figure 14: Average crown score by species. E. *viminalis* are the worst affected by dieback, followed by *E. rubida*. *E. pauciflora*, *E. stellulata* and *E. bridgesiana* were largely unaffected.

Figure 15: Clear species difference: dead *E. viminalis* with healthy *E. pauciflora* behind. Photo: Catherine Ross

Figure 16: Average crown score. Juvenile trees were healthier than adult trees, while there was no difference between dominant or co-dominant trees and suppressed trees.
5.4 Discussion

The findings presented here do not support the hypothesis that sites with greater structural complexity are more resilient to dieback. Despite the fact that the study sites had quite severe dieback, all sites had SCI scores over 50 and all except one (site 7) scored above average compared to the reference sites. Since sites 5, 6 and 7 were compared with forest rather than woodland sites, their scores were reduced. In absolute terms these forest sites are more structurally complex than the other sites (respective scores of 75, 75 and 70), but are around the same or worse relative to the expectation for similar sites. It is important to note that scores at the extreme ends of the spectrum are impossible because the attributes are not independent. For example hollows are more likely to form in large and/or dead trees, so these attributes would be expected to be correlated.

Some of the data can be explained by the presence of dieback. For example, dieback would be expected to increase numbers of dead trees, and as such basal area and quadratic mean diameter would be reduced. These attributes were highly correlated with the severity of dieback. Trees affected by dieback would also be expected to drop more branches and create less litter. Although the amount of woody debris was not correlated with dieback severity, seven of the eight sites had very high scores for woody debris and the eighth was also the least affected (site 8). Litter dry weight scored very low across all sites, and at the sites with the highest scores (sites 5 and 6) most of the litter was acacia pods rather than eucalypt leaf litter. These effects of dieback on structural complexity attributes are likely to mask evidence of the original cause.

All sites scored high to very high for ground (<0.5m) and midstorey (0.5-6m) cover, and this could be explained a number of ways. Firstly, the measurements were taken in spring after several very wet years. Second, the loss of canopy cover due to dieback allows more light to the ground, and there may be less competition for water with the declining overstorey. Third, at the sites that were burnt in 2003 the fire may have stimulated regeneration, particularly of *Acacia* species. This was particularly apparent at site 6 which was dominated by *Acacia* and had a midstorey density almost double that of the neighbouring unburnt area (site 5). One or more of these may be working in combination to produce the very high cover.

The SCI does not allow for scores to be outside the reference range; these are given the same as a ‘high’ score. This means that the Index assumes that very high values for an attribute are still good, and this may not always be the case. It is unclear whether a
midstorey density ten times higher than normal is a positive thing – this could be seen as an environmental imbalance that may in fact decrease structural diversity. In Bell Miner Associated Dieback a dense understorey is thought to attract aggressive Bell Miners which drive out other small birds (Jurskis, 2005). A dense understorey may be the result of fire exclusion which may contribute to dieback by competing with the overstorey (Jurskis & Turner, 2002; Close, et al., 2009). This does not seem to be the case here given that the highest understorey density was found at sites which were recently burnt. Because this is a measurement at a single point in time it is impossible to tell whether the understorey density is a contributing factor or a symptom of the dieback.

Regeneration was low at all sites except sites 7 and 8. Both these sites were burned in 2003 and the age of the young trees seemed to fit with a regeneration event following this fire. Site 6 had also experienced a regeneration event following the fire, but in contrast it was dominated by Acacia rather than Eucalyptus species. Where juvenile trees were present they were much less affected by insect attack, so it is unlikely that the low regeneration scores at other sites were a direct result of dieback. However adult trees affected by dieback have been shown to have reduced reproductive capacity (Landsberg, et al., 1990; Landsberg, 1988b). The Monaro is also a notoriously difficult environment for tree seedlings to establish in, and this is thought to be one of the reasons why it is largely treeless.

There is no evidence that land management has any effect on dieback severity. Unlike other episodes of dieback where grazing land was more affected by dieback than reserves and nearby forested areas, in this case one of the grazed sites (site 3) was healthier than the two TSRs (sites 1 and 2) and similar to the forested sites (sites 5, 6 and 7). The grazed site (site 4, which was not measured because the landholder pulled out) next to site 2 was equally affected by dieback but had clear evidence of grazing, with a much sparser understorey than site 2 and improved pasture. Interestingly, the least affected site was site 8, a forest clearing which had experienced previous cropping and fertilisation. This site was apparently very fertile and wet, and grazed heavily by kangaroos. The site had only scattered large trees and thickets of regrowth around ten years old or younger. This appears to contradict the tree vigour theory, which would predict that trees growing in highly fertile soil should have foliage of higher dietary quality for insects. This site also scored highest on the SCI, despite its apparent simplicity.
A lack of habitat for important predators or parasites has often been thought to contribute to dieback in rural areas (see chapter 2). This explanation seems unlikely in this case, given that all sites scored very highly for understorey cover, that reserves and forest sites were also affected, and that dieback severity was not greatly different across sites with very different understorey densities (Figure 17). The presence of dieback in forested areas that have not experienced clearing would also seem to exclude the isolation theory.

Figure 17: Dutton TSR (left) was severely affected by dieback despite high structural complexity and low disturbance. A grazed site next door (right) was equally affected by dieback. Photos: Catherine Ross

Comparison of neighbouring sites 5 (unburnt) and 6 (burnt) shows the differences as a result of the fire in 2003 (Figure 18). The burnt site had a lower crown score, but this was largely due to a higher number of dead trees, which had apparently been killed in the fire as they had charcoal at the base of the trunks and appeared to have been dead for a considerable amount of time. There was no difference in the severity of dieback in the living trees. Contrary to the prediction that fire exclusion causes understorey proliferation, the fire had stimulated thick regeneration of Acacias. The burnt sites also had higher rates of overstorey regeneration.

Figure 18: Comparison of neighbouring unburnt (left) and burnt (right) sites. The burnt site has a dense understorey dominated by Acacias, but dieback severity did not differ. Photos: Catherine Ross
5.5 Conclusions
Within the dieback affected area, eight paired sites were chosen that differed in their land use or fire history. All but one site received above average structural complexity scores, and there was no correlation between overall structural complexity and dieback severity. Although individual attributes such as basal area and dead trees were correlated with dieback severity, these are more likely to be symptoms of the dieback rather than the cause.

Despite superficially resembling other episodes of rural dieback, the Monaro dieback is not caused by factors relating to land use such as grazing, lack of understorey or isolation. The fire exclusion theory is also unlikely to apply in this case.
Chapter 6: Climate

6.1 Introduction

Climate change is already occurring in eastern Australia, with warming temperatures, increasingly variable rainfall, and more extreme events such as droughts, floods and heatwaves (Murphy & Timbal, 2008). Climate and extreme events such as drought have often been suspected as a cause of dieback (Allen, et al., 2010; Auclair, 1993). The Monaro region already experiences low and highly variable rainfall, and the coincidence of the Monaro dieback with one of the worst recorded droughts (CSIRO, 2010) in eastern Australia does suggest a possible relationship.

Insects are extremely sensitive to climate, so even small changes could result in a large response (Stange & Ayres, 2010). Climate change may have a direct effect on the reproduction and development of the weevil itself, or it may affect the interactions between the weevil and its predators or host trees (Figure 19). Climatic variation is thought to be responsible for a range of insect outbreaks, including phasmatids (Readshaw, 1964), scarab beetles (Heatwole & Lowman, 1986) and jarrah leaf-miners (Mazanec, 1980). Outbreaks of psyllids across Australia have been related to large fluctuations between wet and dry season rainfall, which is thought to cause water stress in the host trees and result in increased foliar nutrient content (White, 1969).

Figure 19: Climate may directly affect the insect itself, or may influence the interactions between the insect and its predators or host plants. Image from Stange and Ayres (2010)

This chapter will examine historical climate data from the Monaro region, to look for trends or patterns that may suggest a relationship between climate and the recent dieback. Long term changes in temperature and rainfall may have an effect, as well as seasonal changes in the distribution of rainfall or extreme events such as drought. In addition, two methods will be used to estimate the effect of climatic conditions on the trees; White’s Stress Index (White, 1969) and the GROWEST (growth estimation) Index (Laughlin, et al., 2007).
6.2 Methods

Monthly climate data for the region were acquired from Professor Michael Hutchinson, using monthly climate surfaces interpolated from Bureau of Meteorology weather stations using the ANUSPLIN software (Hutchinson, 2004). This software has been applied to climate interpolation in many regions around the world (New, et al., 2002; Hijmans, et al., 2005; Hutchinson, et al., 2009). Ten locations were chosen, at the study locations from the preceding chapter and around the region surveyed in Chapter 4 (Figure 20). Rainfall data were available from 1920 to 2011, while temperature, evaporation, and solar radiation data were available from 1970 to 2011. Rainfall and temperature data were analysed visually to look for long-term annual, seasonal or monthly patterns and trends.

6.2.1 White’s Stress Index

White’s Stress Index is based on the theory that tree stress is caused by large fluctuations in rainfall; specifically a period of high rainfall during the growing season which drowns the roots, followed by particularly dry conditions that compromise the surviving roots’ ability to supply the trees with adequate water. It is expressed as an annual Stress Index (SI), where high scores indicate a wetter than average wet season followed by a drier than average dry season, and low scores indicate the reverse (White, 1969).

The SI was calculated for each year from 1921 to 2011, as per White (1969; 1986). The Index is the difference between rainfall in the wet season and following dry season, expressed as standard normal deviates about the long-term averages. It has been presented as a three-year running average to smooth out annual fluctuations and highlight the cumulative effect of climate over several years. Periods with positive or increasing values of the SI are considered high stress. The wet and dry season were determined by examination of long-term monthly rainfall averages.

6.2.2 GROWEST Index

The GROWEST Index (GI) was developed initially by Fitzpatrick and Nix (1970). It combines the effects of light, temperature and soil moisture to give an estimate of plant growth as a fraction of the maximum potential growth under optimal conditions (Laughlin, et al., 2007; Nix, 1981; Hutchinson, et al., 1992). Seasonal summaries of these growth indices have been used to characterise agro-ecological conditions around the world and for Australia (Hutchinson, et al., 1992; 2005). Low values for the GI indicate periods where climatic conditions were particularly stressful.
Figure 20: Map of Monaro region showing location of ten sites for climate analysis

<table>
<thead>
<tr>
<th>Site</th>
<th>Average annual rainfall (mm)</th>
<th>Average max temp (°C)</th>
<th>Average min temp (°C)</th>
<th>Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>536.28</td>
<td>17.87</td>
<td>4.67</td>
<td>900</td>
</tr>
<tr>
<td>2</td>
<td>535.83</td>
<td>17.70</td>
<td>4.66</td>
<td>900</td>
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<td>3</td>
<td>592.88</td>
<td>16.61</td>
<td>4.11</td>
<td>900</td>
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<tr>
<td>4</td>
<td>568.61</td>
<td>17.57</td>
<td>4.74</td>
<td>850</td>
</tr>
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<td>5</td>
<td>618.68</td>
<td>16.65</td>
<td>3.98</td>
<td>950</td>
</tr>
<tr>
<td>6</td>
<td>582.90</td>
<td>16.91</td>
<td>4.21</td>
<td>1000</td>
</tr>
<tr>
<td>7</td>
<td>581.25</td>
<td>16.95</td>
<td>4.43</td>
<td>900</td>
</tr>
<tr>
<td>8</td>
<td>712.21</td>
<td>16.00</td>
<td>4.02</td>
<td>950</td>
</tr>
<tr>
<td>9</td>
<td>737.12</td>
<td>15.74</td>
<td>3.80</td>
<td>1150</td>
</tr>
<tr>
<td>10</td>
<td>869.99</td>
<td>14.39</td>
<td>3.16</td>
<td>1300</td>
</tr>
</tbody>
</table>

Table 3: Rainfall and temperature at ten sites across the Monaro region (locations shown in Figure 20). Sites 1 to 7 fell in the dieback affected tablelands area and were very similar climatically, while sites 8, 9 and 10 (shaded) were cooler and wetter on average and fell in the higher country to the north and west outside the affected area.
The Growth Index (GI) is the product of the Light Index (LI), Thermal Index (TI) and Soil Moisture Index (MI). Each index ranges from 0 to 1, where 0 indicates conditions under which plant growth cannot occur and plants are likely to be under stress or in a dormant state, and 1 indicates optimal conditions for plant growth where plants are growing at their maximum rate (assuming that other factors are not limiting). The LI is calculated using solar radiation levels, the TI is a combination of average maximum and minimum temperatures, and the MI is based on rainfall and evaporation rates as well as soil depth and type.

The GROWEST model is maintained at the ANU Fenner School of Environment and Society (Hutchinson, et al., 2004). The model was run using solar radiation, temperature, rainfall and evaporation data from 1970 to 2011 for the same ten sites around the Monaro region (Figure 20). Calculations for the model were based on C3 microtherm plants, clay loam soil type and soil depth of 150mm.

6.3 Results
Examination of the climate data for the ten sites showed two distinct climatic regions, which will be referred to here as the tablelands and mountain regions (see Table 5). The tablelands region, which coincides with the dieback affected area, included seven of the ten sites which were very similar climatically (Table 5, unshaded). The three mountain sites to the north and west of the region were cooler and wetter and were outside the dieback affected area so have been excluded from analysis (Table 5, shaded). The difference in climate between these regions is likely to account for the change in species composition.

Mean annual temperature across the tablelands sites was around 10-11°C, with mean minimum temperatures around 4°C and mean maximum temperatures around 17°C. Mean annual rainfall ranged from around 530-620mm (Table 5). Variation was extremely high for both annual and monthly rainfall, particularly in summer.

As variations in climate were consistent across the tablelands sites one representative site (site 1) was chosen to be presented here, based on its location near the centre of the affected area.

6.3.1 Temperature and Rainfall Patterns and Trends
The climate of the Monaro has been getting warmer and drier (Figure 21, 22). In the last ten years, the average annual temperature was warmer than the long term average (1970-2011) by 0.4°C. Average annual rainfall for the last decade was 480mm, which was lower than the long term average (1920-2011) by 55mm.
The distribution of rainfall throughout the year has also changed. Examination of monthly averages over the whole 90 year period showed that rainfall is distributed fairly evenly through the year, with a wet season from November to February, and a dry season from May to August (Figure 23). However, in the last 20 years the wet season was slightly wetter on average, while autumn was much drier (approx. 25-30%). This change has shifted the dry season earlier in the year and increased the difference between the wettest and driest parts of the year.

Figure 21: Trend in annual average maximum and minimum temperature in the Monaro region. There has been a slight increase in temperature over the period from 1971 to 2011.

Figure 22: Trend in annual rainfall in the Monaro region. There has been a decrease in annual rainfall over the period from 1921 to 2011.
Figure 23: Rainfall distribution - when compared to the long-term average from 1920-2011, the last two decades have experienced a change in rainfall distribution. Autumn rainfall has decreased, while late spring and summer rainfall has increased.

6.3.2 White’s Stress Index
Over the 90 year period from 1921 to 2011, there was a general upward trend in the Stress Index (SI), and periods of very high stress (SI > 1) continuing for several years have occurred in the early 70s and mid 90s (Figure 24a). The last decade was the longest period with scores consistently above zero; however a slightly shorter period occurred in the 1970s which had higher scores on average.

To account for the change in seasonal distribution of rainfall (Figure 23), the SI was also calculated for a three month wet period from November to January and a dry period from March to May (Figure 24b). This analysis gave slightly different results: peaks above 1 occurred in the mid 1930s, early 70s, mid 90s and in 2006. The large peak in the 70s was smaller and shorter in length, and the scores for the last two decades were higher on average and consistently above zero. This indicates that the recent changes in rainfall distribution have put trees under greater stress, according to White’s Index.
6.3.3 GROWEST Index

The Monaro region has a relatively low average annual GI at around 0.25, ranging from close to zero in February to around 0.6 in September/October. GI is determined by the interaction between light, temperature and moisture shown in Figure 25. High temperatures are the main limiting factor during summer, while cold temperatures in winter mean that the higher soil moisture levels have little effect. The main growing periods occur in spring and autumn when temperature is optimal but moisture is the limiting factor, and the high variability of the MI also accounts for most of the variation between years (Figure 25, 26). The recent drop in autumn rainfall results in a 10% reduction in growth during that period (Figure 25b).
Figure 25: The Growth Index (GI) is determined by the interaction between light (LI), temperature (TI) and moisture (MI). (a) 1970-1990 (b) 1991-2011. Most growth occurs during spring and autumn. The drop in autumn rainfall in the last two decades is clearly visible.

Over the study period there was a downward trend in the annual GI, due to decreases in both MI and TI (Figure 26). The recent drought corresponded with below average GI scores, and during this period growth rates were as low as half the normal rate. The next lowest point occurred in the early 1980s, which also corresponded with a severe drought, but of much shorter duration.
Figure 26: Light, Temperature, Moisture and Growth Index-1971-2011: 12-monthly averages calculated monthly. Over the period from 1971 to 2011, there has been a slight decrease in the Growth Index. Low values for GI in the last decade correspond with the drought, and the period since the onset of dieback.
6.4 Discussion
Examination of climate data for the Monaro region showed general warming and drying trends over the last 40 and 90 years respectively. The Millennium Drought, which lasted from 2001 to 2009, is considered to be one of the worst droughts on record with rainfall well below average, particularly in autumn (Van Dijk, et al., 2013). These changes are consistent with those predicted under climate change in south-eastern Australia (CSIRO, 2010; Murphy & Timbal, 2008).

6.4.1 Direct Effects on Weevil Reproduction or Development
These changes in climate may have a direct effect on insect populations. Warmer temperatures throughout the year could increase growth and survival rates in the weevil larvae, and shorten the winter hibernation period (Tooke, 1953). This could allow the weevils to proliferate faster, or even to complete an extra generation within the growing season (Santolamazza-Carbone, et al., 2006).

On the other hand, low soil moisture has been shown to decrease survival of pupae developing in the soil (Tooke, 1953). Most of the drying has occurred in autumn when the second generation are in the pupal stage, so this may affect the number of adults emerging before winter. Drought also limits the availability of new growth for the weevil.

6.4.2 Effects on Predators or Parasites
There is some evidence to suggest that Anaphes nitens is less effective in drought when fewer weevil eggs are available (Tooke, 1953). A. nitens has a short life span and is entirely dependent on the presence of weevil eggs, so if none are available for an extended period the population can drop dramatically. The weevil has a much longer life span and can delay oviposition until new growth is available, so it responds quickly to improved conditions, and the delay in the wasp’s response to this can provide a window for the weevil to proliferate unchecked (Tooke, 1953). However, prolonged drought conditions would be expected to have a detrimental effect on the weevil’s reproduction and development.

6.4.3 Tree Stress
The Monaro has a relatively harsh climate which limits plant growth, as indicated by the low average growth index. Eucalyptus viminalis normally grows in low-lying areas with deep soils, and its distribution is strongly related to rainfall with the preferred range being around 500-1700mm (Figure 27) (Florabank, 2013). This species is on the edge of its range, and it is somewhat surprising that it can grow at all in such a dry environment. During the Millennium Drought (2001-2009), rainfall dropped to around 440mm on average, well
below the normal range preferred by *E. viminalis*, and over a prolonged period this would be expected to cause significant stress. The only climatically comparable region within the *E. viminalis* range is the Tasmanian midlands where dieback has also been linked to drought (Doyle, 2005).

![E. viminalis distribution vs. annual precipitation. Black dots are locations where *E. viminalis* have been recorded. The Monaro region is circled, and is clearly much drier than the surrounding region. *E. viminalis* distribution is strongly related to moisture (Map created using the Atlas of Living Australia, http://www.ala.org.au/)](image)

The distribution of rainfall throughout the year has also changed, with more rainfall now occurring in spring and less in autumn than 90 years ago, increasing the difference between the wet and dry season. According to White’s Stress Theory, this difference between wet and dry season rainfall causes tree stress, so it may be expected that tree stress has also increased over this period and may be a contributing factor in the current dieback (White, 1969).

Both the SI and GROWEST Index indicated that the recent dieback coincided with conditions which were likely to be stressful for plants. There was an increasing trend in the SI and a decrease in the GI, and the last decade had both consistently high SI scores and low GI scores. This indicates that climatic conditions have become less favourable over time according to both indices.
There are very few theories in the literature that try to explain why tree stress may cause insect outbreaks. White’s theory hypothesises that high SI values result in increased foliar nutrient content, which benefits insects as they are limited by nitrogen availability. Several lab and field studies have supported this theory; in 1983 a study by Landsberg and Wylie found that dieback trees had higher nutrient levels as well as higher rates of insect attack. However, the studies by White (1969; 1986) and Landsberg and Wylie (1983) have concerned dieback episodes associated with senescence feeders such as psyllids and scarab beetles. These insects feed preferentially on mature and senescing foliage and are therefore likely to benefit from the increased nutrient content in the leaves of stressed trees (Price, et al., 1990; White, 2009). However, plant stress also causes wilting, increased leaf toughness and reduced growth (Landsberg, 1990c), all of which have a negative effect on herbivores and in particular those that require new flushing foliage i.e. flush feeders (Price, et al., 1990). Since the eucalyptus weevil is a typical flush feeder (Landsberg & Cork, 1997), the tree stress theory as put forward by White does not seem to be a likely explanation.

If climatic tree stress did contribute to the dieback, we might expect that the much larger peak in the SI during the 1970s should have resulted in severe dieback; yet there is no evidence for a similar event at that time. This peak is the result of very high wet season rainfall, rather than the low dry season rainfall experienced recently. Interestingly, other areas in eastern Australia did experience dieback during that period; in south-eastern Queensland an outbreak of leaf-feeding insects occurred in 1974, immediately following a huge spike in the SI (Landsberg & Wylie, 1983). The New England dieback also began around that time and continued until the early 80s (Mackay, et al., 1984). Similarly, the GI was very low in the early 1980s but there is no evidence that this resulted in dieback. This drop corresponded with an extreme drought at the time, but it was much shorter in duration than the more recent Millennium Drought. It may be that the Monaro dieback is the result of chronic rather than acute water stress.

Since the drought broke, the Monaro region has experienced several very wet years; however this has not resulted in any improvement or recovery. It is possible that a ‘tipping-point’ or threshold has been reached, beyond which trees cannot recover; or that the feedback loop effect of repeated defoliation continues the cycle well beyond the initial cause.
6.5 Conclusions

The climate of the Monaro region is particularly harsh, with low and unreliable rainfall and extreme temperatures limiting plant growth. Examination of historical climate data shows that in recent decades the region has experienced one of the worst droughts on record, along with an unprecedented drop in autumn rainfall and steadily increasing temperatures. These conditions are likely to cause tree stress and affect the interactions between insect populations and their predators and hosts.

Climate has the potential to affect every part of an ecosystem, so even slight changes are expected to have significant and far-reaching effects. In an already marginal environment, these changes may have been enough to cross an ecological threshold, beyond which the Monaro region is no longer suitable for *E. viminalis*. Although there is only circumstantial evidence to link the recent drought and climate change with the Monaro dieback, the timing and scale of the dieback is consistent with a climatic origin.
Chapter 7: Discussion and synthesis

7.1 Introduction
Dieback is often referred to as a disease of complex aetiology – the result of many factors which interact in such complicated ways that it is impossible to provide a sufficient diagnosis (Old, 2000). Although many causes and mechanisms have been suggested, most cases remain at least somewhat mysterious. This study of dieback in the Monaro region has involved investigation into a range of possible factors that may play a part in this disease, with each chapter acting as a separate enquiry with its own methods, findings and discussion. This chapter will bring together the evidence presented in the last four chapters and apply it to the theories put forward in the literature review. Box 1 gives a summary of each chapter and its most important findings.

7.2 Conceptual Diagram
The extreme complexity of dieback is represented by the conceptual diagram presented in Chapter 2, which summarises the many interacting factors that have been suggested in the literature to relate to dieback. Each of the five possible mechanisms put forward in the literature review are discussed below in light of the evidence presented in the four preceding chapters. Parts of the diagram have now been shaded in grey to indicate that they are not supported by the evidence, either from the literature or my own field studies (Figure 28).

Box 1: Summary of findings by chapter

In Chapter 3, the weevil that is responsible for the Monaro dieback was positively identified as a currently undescribed member of the Gonipterus genus, previously known as Gonipterus scutellatus and commonly known as the Eucalyptus weevil. This weevil is a specialist flush feeder and its life cycle is typical of a latent species.

In Chapter 4, I presented the results of a road survey of the dieback affected area. I was able to map the extent and severity of the dieback and look for spatial patterns. The edges of the dieback are defined by changes in species composition, and within the affected area all *E. viminalis* are affected. No obvious spatial patterns were found related to land use, understorey density or aspect.

Chapter 5 compared structural attributes at eight paired sites with differing land uses or fire histories, in order to test the hypothesis that structural complexity increases resilience to dieback. The severity of dieback was not related to structural complexity, and there was no difference between grazed and ungrazed or burnt and unburnt sites.

Chapter 6 looked at climatic factors relating to dieback. In the last few decades the climate of the Monaro has become warmer and drier with more variable rainfall, and the distribution of rainfall throughout the year has also changed. Both the Stress Index and the GROWEST Index indicate that conditions have become less favourable for plant growth.
Figure 28: Dieback conceptual diagram – factors which are not supported by the evidence have been greyed-out.
7.2.1 Missing or Ineffective Parasite or Predator
There is some controversy about the extent to which predators and parasites control insect populations (Price, et al., 1990). For latent species such as the eucalyptus weevil, the main limiting factor is thought to be the availability of suitable oviposition sites. However the success of the biological control of the eucalyptus weevil in overseas plantations suggests that the egg-parasitoid *Anaphes nitens* may exert a strong control over the weevil population (Tooke, 1953). In this case, the weevil is in its native habitat, so one would expect that its natural enemies should be present, unless habitat is missing, there is competition (as in BMAD) or unfavourable climatic conditions.

There is no evidence to suggest that a lack of habitat is related to the Monaro dieback. The road survey and SCI showed that the presence or absence of understorey had no effect on the severity of dieback, and several species of birds were observed at all sites, even the most severely affected. A study of rural dieback near Canberra found that egg parasitoids were present at affected sites, even those that had very poor floristic diversity (Landsberg, et al., 1990). My attempt to measure parasitism rates unfortunately failed, however *A. nitens* is entirely dependent on the weevil for its development and so should not be affected by a lack of habitat as long as weevil eggs are present (Tooke, 1953). Where *A. nitens* has been introduced to control the eucalyptus weevil, it has been shown to have an excellent ability to respond to fluctuations in the host population (Tooke, 1953; Hanks, et al., 2000); however its efficiency can be reduced in drought conditions (Tooke, 1953).

Although the Monaro dieback cannot be attributed to BMAD, it is possible that competition with another species could drive out the weevil’s natural enemies. The only way to rule out the possibility that the Monaro dieback is caused by a missing parasite or predator is to confirm their presence by conducting bird and insect surveys and measuring predation and parasitism rates.

7.2.2 Isolation
In rural dieback, isolated paddock trees are often more affected by dieback than those in nearby woodland or forest remnants (Mackay, et al., 1984). Although the Monaro bears a resemblance to other cases of rural dieback, there is no evidence of density dependence in this case; the trees tend to grow in patches on ridges and hill tops so isolated paddock trees are rare, and trees in woodlands or forests are equally affected.
7.2.3 Improved Quality or Availability of Food
The tree vigour and tree stress theories are widely considered to be two ends of a spectrum: at one end are insects which normally feed on mature or senescing tissues and therefore benefit from plant stress, and at the other end are flush feeders which benefit greatly from an abundance of vigorous new growth (White, 2009).

Tree vigour
As a flush feeder, the eucalyptus weevil requires new growth to feed and reproduce and the limited availability of this resource exerts strong control on the population. Therefore conditions which increase the quality or quantity of new growth could result in an outbreak; for example nutrient enrichment from fertilisation or from livestock is thought to increase foliar nutrient content and insect feeding rates (Landsberg, et al., 1990; Landsberg, 1990c). However there is no evidence that the Monaro dieback is related to land use. Fertilisers are rarely used in the region, and the road survey and site comparisons showed that TSRs and reserves were just as badly affected by dieback as the surrounding grazing land. In Chapter 5, the only site with a history of fertilisation was also the least affected (site 8).

Tree stress
Dieback is almost always assumed to be the result of stress, which can be caused by a range of factors (Manion, 1981). Several of these can be eliminated by simple observations from the road survey; there is no evidence that salinity, pollution, fungal infection, or mistletoe infestations are major problems on the Monaro.

Agricultural land management practices have been implicated as stress factors in rural dieback, in particular nutrient imbalances from fertilisation and manure, soil compaction and physical damage from livestock or machinery, or competition with improved pastures and crops (Landsberg & Wylie, 1983). Although much of the Monaro region is used for agriculture, I did not find any difference in the severity of dieback between grazing land and nearby TSRs or reserves. It would also be expected that if stress was the cause of the dieback, suppressed trees would be more affected than dominant or co-dominant trees, but this was not the case (Figure 16).

Fire exclusion has also been suggested as a cause of tree stress, through competition with understorey and soil nutrient imbalance. Fire frequency on the Monaro is thought to have decreased since European settlement (Jurskis, et al., 2006), but a comparison between neighbouring burnt and unburnt areas showed no difference in the severity of dieback. In
fact, contrary to the prediction that long unburnt areas have a much denser understorey (Jurskis & Turner, 2002), the density was almost twice as high in the burnt area, probably due to the fire stimulating regeneration of Acacias. More frequent burning may still have the effect of suppressing the understorey, but this seems irrelevant given that the road survey and the site comparisons found understorey density was unrelated to dieback severity.

Tree stress may also be caused by weather or climatic factors. The climate of the Monaro has become warmer and drier over the last few decades, and the distribution of rainfall throughout the year has also changed. Both White’s Stress Index and the GROWEST Index show that the climate is becoming increasingly stressful, particularly in the last decade.

7.2.4 Climate

There is strong circumstantial evidence that climate has played a role in the Monaro dieback. The timing of onset coincided with one of the worst droughts on record, during which rainfall was well below average, particularly in autumn. In addition, the dieback has occurred in an area which is particularly dry in comparison to the rest of the range of *E. viminalis* (Figure 27), and within the affected area, the most severe dieback corresponds with the lowest rainfall (Figure 10). The large scale of the dieback is also consistent with a climatic cause, while other possible explanations such as land use or fire exclusion have been largely ruled out.

At the field day held by Greening Australia in 2011, some local landholders connected the recent drought with the onset of dieback, and had observed signs of water stress in affected trees. Some also reported the presence of healthier trees in river valleys and recovery following rain (see Appendix 2). This only evidence of this observed during my study was a single tree in an apparently well watered garden near Dalgety which was relatively healthy, and several trees at site 8 (see Chapter 5) which were growing in very moist conditions and were healthier than the trees in the surrounding forest. There was no obvious relationship with aspect, and there was no evidence of recovery despite three consecutive very wet years since the end of the drought.

Further, the mechanism for how drought would cause dieback is unclear. As discussed above, the eucalyptus weevil is a flush feeder and more likely to benefit from vigorous growth than from trees under stress. It has also been suggested that stressed trees have reduced growth and therefore suffer greater damage from the same insect burden (Tooke,
1953), but again the lack of new growth would be expected to impact negatively on the eucalyptus weevil.

The Monaro has also experienced an increase in temperature as well as reduced rainfall in recent years. This change would be expected to increase growth and survival rates of the weevil larvae, and this in addition to an extended growing season could allow for additional generations in a year and result in huge population increases (Santolamazza-Carbone, et al., 2006). However this increase would be expected to be kept in check by the egg parasitoid A. nitens, which has been shown to respond very quickly to the host population (Santolamazza-Carbone, et al., 2009; Tooke, 1953). There is some evidence to suggest that A. nitens is less effective in drought (Tooke, 1953).

It is also possible that the dieback was instigated by another insect altogether, which has since dropped to normal population levels. In 2008, Dr. Roger Farrow noticed large numbers of gumleaf skeletonisers (Uraba lugens) on dieback affected trees when driving through the Monaro region (Farrow pers. comm.). Outbreaks of U. lugens have been observed during droughts in the Riverina, and are thought to be due to the fact that under dry conditions the larvae are free from a fungal disease which normally controls the population (Farrow pers. comm.) The eucalyptus weevil may simply be taking advantage of the epicormic growth produced by trees following severe defoliation by U. lugens.

As climate acts on whole ecosystems rather than discrete parts, it is likely that the cause of the dieback is a combination of factors. Further research will be needed to establish the effects of climate on the weevil, its host trees and natural enemies. This may include observing emergence times and growth rates under warmer temperatures, measuring soil and foliar nutrient levels under stressful or benign conditions, conducting bird and insect surveys, and measuring parasitism and predation rates.

7.3 Limitations
Studies of dieback are almost always limited by a lack of information about the timing of the onset of the problem. Because it progresses so slowly, dieback can often be overlooked until it is too late, and historical or anecdotal data is patchy and unreliable. An honours project conducted over the course of a year can only hope to provide a snapshot in time. It is almost impossible to diagnose the cause of dieback without having detailed information about the conditions that may have contributed to it at the time.
Other studies of dieback have usually compared dieback trees with nearby healthy trees. In this study this method was not possible, as all trees within an area were equally affected (except different species). This lack of within site differences and patterning of dieback makes diagnosis extremely difficult. It is possible that differences may have been present when the dieback first started, but as it has progressed the weevils exhausted the most palatable food and moved on to less attractive foliage.

The problems associated with studying dieback highlight the importance of broad scale surveys and regular monitoring of tree health, to identify the moment of onset and track the progression of the disease.

7.4 Implications
If the dieback continues at the current rate it seems inevitable that *Eucalyptus viminalis* (and possibly *E. rubida*) will disappear entirely from the Monaro region. Although juvenile trees seem to be more resistant to attack, there is very little regeneration and once they reach a certain age and begin producing adult foliage it is assumed that they will also succumb. As *E. viminalis* is the dominant species in most of the region, this will have very serious consequences.

Much of the Monaro is naturally treeless or has been cleared since European settlement, so the remaining patches of *E. viminalis* woodland are important refuges for wildlife to move across the landscape. *E. viminalis* is one of very few species of eucalypt preferred by koalas, and one local landholder I spoke to had already noticed a drop in koala numbers since the dieback started (O’Brien pers. comm.). The patches of woodland are also very important as shelter for stock and to prevent erosion, not to mention their aesthetic value.

7.4.1 Will it spread?
Anecdotal evidence from locals (Murdoch pers. comm., Appendix 2) suggests that the dieback may have spread from an original starting point around Berridale. This theory is supported by observations made on the road survey that the most severe dieback is in the middle of the affected area between Cooma and Berridale, and severity decreases toward the edges. However, most of the boundaries are defined by a change in species composition, so it is possible that the dieback has reached to almost its full extent. *E. viminalis* has a very large distribution throughout most of eastern Australia, but they are far more dominant on the Monaro than in the surrounding areas. It therefore seems unlikely that the Monaro dieback will spread much further beyond its current extent, for example
into Kosciuszko National Park which is dominated by snow gums (*E. pauciflora*) that appear to be immune to weevil attack.

### 7.2.2 Dieback Around the World
The occurrence of dieback around the world does indicate that it may have a common cause, especially given the similarities between episodes and the recent increase in frequency and severity (Allen, 2009). In particular, insects often appear to play a major role in dieback, and the symptoms and progression of the disease can be strikingly similar despite the range of species and ecosystems involved. Although each episode has unique contributing factors, climate change may provide an explanation for the occurrence of dieback around the world, even in relatively undisturbed areas (Allen, 2009). It is very likely that dieback will become more common under climate change in the future, and it will be increasingly important to be able to predict, prevent, manage and rehabilitate affected areas.

### 7.2.3 Ecosystem Shift Under Future Climate Change
Climate change is expected to cause changes in ecosystem composition and distribution, as species or communities shift to follow the changing climate. These changes often lag behind the rate of climate change because of what is known as ‘inertia’; the presence of long-lived organisms such as trees that prevent the establishment of invading species (Jentsch, et al., 2007). The inertia of a system can be overcome by a disturbance that causes premature mortality of these long-lived organisms, such as an extreme weather event, or in this case an insect outbreak causing dieback. If climate change is the cause of the increase in insect-related dieback events around the world, this may increase the speed of ecosystem shift predicted by current climate models.

As the climate warms, species may be expected to shift towards the poles or to higher altitudes to follow their ideal temperature niche. However this is a very simplified view, as temperature is not the only factor affecting species distributions. The position of the Monaro region in a rain shadow gives it a unique climate that is much drier than the surrounding region, so as the temperature warms, species moving from wetter areas on the coast or to the north may not be able to survive. In fact, the most suitable species for the future climate of the Monaro may come from more arid regions on the western side of the Snowy Mountains, and human intervention may be needed to assist the migration of these species.
7.5 Management Recommendations

This thesis aimed to provide Greening Australia with recommendations for the management of the Monaro dieback. Managing dieback may have a range of aims, whether to improve the health of affected trees, prevent dieback from spreading to healthy trees or neighbouring areas, rehabilitate severely affected areas, or prevent a recurrence in the future or elsewhere.

Current recommended management of dieback usually involves changing land management practices, for example reducing grazing pressure to allow regeneration and prevent nutrient enrichment and soil compaction (Close, 2003; Platt, 1999). As part of this project I have put together a fact sheet for Greening Australia staff, stakeholders, partners and landowners, outlining current recommendations for dieback prevention and management (Appendix 7). Most of these recommendations would be the same for any degraded landscape, and aim to increase biodiversity and resilience. These actions should not be abandoned because they are known to be beneficial in other situations; however the evidence suggests that they would be unlikely to prevent or improve dieback symptoms in this case.

Treatment with stem-injected pesticides has been shown to be successful in preventing insect damage and allowing trees to recover in the short term (Murdoch, pers. comm., Appendix 1). However, this method is very expensive and labour intensive, and must be reapplied every four years as the effects of the pesticide wear off. Using stem-injected pesticide is impractical on the large scale of the dieback, but it may still be useful for protecting trees that have particular aesthetic or other importance e.g. trees in gardens. It may also be beneficial to treat selected trees to act as seed sources, which will hopefully contribute to regeneration and allow the species to recover if conditions become more favourable in future.

Fire exclusion is unlikely to be the cause of the Monaro dieback, but it is becoming widely recognised as a form of disturbance in fire-prone landscapes (Jurskis, 2005b). While a single burn is not expected to have any effect on dieback, it may help to encourage regeneration. However, fire may also damage trees that are already under stress from dieback, so it should be used with caution.

If the underlying cause of the Monaro dieback is climatic, it would seem that very little can be done to fix the current problem or prevent it happening in the future. It may be that the environment is simply no longer suitable for *E. viminalis*, and that the species will
eventually disappear from the area. Currently, *E. viminalis* is one of the main species used by Greening Australia for revegetation projects in the Monaro region, but it may be that greater success would be achieved using other species that are more resilient to insect attack and adapted to a warmer and drier climate. However, it is not recommended that planting *E. viminalis* should stop altogether as conditions may change in the future and allow the species to recover.

Unfortunately, predicting when and where dieback may occur under future climate change is extremely difficult, but regular monitoring of tree health may identify large-scale patterns. There are significant gaps in the current knowledge about the complex feedback and interactions between climate and ecosystems, and the climatic thresholds of trees and other organisms (Allen, 2009; Allen, et al., 2010). However the most sensitive regions are likely to occur in marginal areas or at the ecological boundaries between species or communities (Jump, et al., 2006).
Chapter 8: Conclusions

The research I have undertaken as part of this honours project has contributed significantly to the available knowledge about the Monaro dieback, which previously had received very little attention despite the extent and severity of the problem. Although it displays many similarities with other episodes such as the New England dieback, the Monaro dieback seems to be a unique case which is likely to be the result of complex interactions between multiple factors.

Like many cases of dieback, the cause of tree decline on the Monaro is repeated defoliation by an insect, in this case the eucalyptus weevil (*Gonipterus* sp.). This relationship is clear from the fact that the dieback only affects eucalyptus species which are the weevil’s preferred hosts, and symptoms are improved after treatment with stem-injected pesticides. Given that the weevil is a typical latent species, it is unlikely that this is simply a cyclic outbreak but must have an underlying cause.

Four theories were discussed in the literature review, which have been put forward to explain higher rates of insect attack in previous dieback episodes:

- Missing or ineffective parasite or predator
- Isolation
- Increased quality or availability of food (tree stress and tree vigour)
- Climate (direct effects)

Through this thesis, I have aimed to explore evidence for or against these theories, from literature and from observations and measurements in the field which may contribute to our understanding of the cause of the Monaro dieback.

From the evidence put forward here, I have concluded that the Monaro dieback is likely to be related to recent changes in climate, including the Millennium Drought. However, this evidence is mainly circumstantial and the exact mechanism by which climate leads to increased insect attack and tree mortality is still unclear. Further research will be required to explore the possible explanations and provide support for a direct causal relationship.

The lack of any relationship between dieback and differences in land use or fire history suggests that current management practices aimed at increasing structural complexity are
unlikely to be effective. However these actions should not be abandoned and trials of potential replacement species should be undertaken.

If climate is the underlying cause of the Monaro dieback, and potentially other episodes of dieback around the world, this could have serious implications for the future. The potential shifts in ecosystem composition and loss of biodiversity as a result of dieback will have a severe impact on both a local and global scale. Understanding the relationships between the climate, insects, and their predators and host plants will be vital to predict the effects of climate change on ecosystems and to manage the changes we may face in the future.
References


CSIRO, 2010. *Climate variability and change in south-eastern Australia: A synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative*. s.l.:SEACI.


Huber, J. & Prinsloo, G., 1990. Redescription of Anaphes nitens (Girault) and description of two new species of Anaphes (Haliiday) (Hymenoptera: Myrmariidae), parasites of


Loch, A., 2006. Phenology of Eucalyptus Weevil, Gonipterus scutellatus Gyllenhal (Coleoptera: Curculionidae), and Chrysochelidae beetles in Eucalyptus globulus plantations in southwestern Australia. *Agricultural and Forest Entomology*, Volume 8, pp. 155-165.


**Personal Communication**

Farrow, Dr. Roger – CSIRO entomology (retired)

Freudenberger, Dr. David – Australian National University, former Greening Australia Chief Scientist

Murdoch, Neil – University of Sydney

Oberprieler, Dr. Rolf – CSIRO entomology

O’Brien, Pam – landowner, NSW Parks and Wildlife Service

Rudd, Maryanne and Brendan – landowners
Appendices

Appendix 1: Stem injected pesticide trial results (Murdoch and Ingram 2010, University of Sydney)

Application of stem-injected pesticides to affected trees improved tree health in comparison with paired untreated trees. Treated trees began to recover while many untreated trees died within the study period.
Appendix 2: Notes from Greening Australia field day at Dalgety, 18th March 2011

Local Observations/Theories

- Drought
- Lack understory & birds
- Insect attack - Christmas beetles & grubs
- Certain Eucalypt species
  - E viminalis, white gum, E. rubida
- Soil health
- Grazing vs. fencing
- Mid to Old trees but some young trees affected too (some very young).
- Around for about 5 years
- Patchy
- Variable drought tolerance
- Wetter season – stalled decline
- Deaths mainly over past 3-4 years
- Winds/shelter – exposed trees more affected??

Is the Research Relevant?

- Possums + Koalas – probably not
  - Eagles nesting – some local observations of those trees affected
- Fertiliser & pasture improvement – probably not as not relevant in most affected areas
  - Sheep camps do increase soil nutrients
- Frost – mainly occurring on hills rather than frosty hollows
- Water logging – definitely not!
- Mistletoe – not a big issue locally
- Fire – lack of regen through burning off
  - Is viminalis fire sensitive?
  - Tussock “cool” burns from the old days, leaching nutrients?
- Soil type
  - Basalts – dieback
  - Slate/shales – regrowth
  - Granites - ?
- Salinity – not a problem
- Phytopthera/fungi – not likely as such a dry area

What causes Dieback?

<table>
<thead>
<tr>
<th>STRESS</th>
<th>Immediate</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insect Attack</td>
<td>Predators/small birds (noisy miners)</td>
<td>Fertiliser/pasture improvement</td>
</tr>
<tr>
<td>Leaf Quality (NP)</td>
<td></td>
<td>Fire?</td>
</tr>
<tr>
<td>Soil</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water – Infiltration</td>
<td></td>
<td>Drought</td>
</tr>
<tr>
<td>Fungi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Group Questions:

1. When did you first notice changes in tree health?
2. What did you notice?
3. What is that tree health like now?
4. Was the change gradual, quick, episodic, continuous?
5. What is the piece of information that would best assist you to manage tree health on your property?

Group One observations:

1. Around 6 years; since 2003 fires
2. Leaves mined, white growth on leaf, gradual defoliation, regrowth after rain, young trees died first. saplings falling over
   Some have borer holes, others with healthy trunks when felled
3. Mostly dead, rest not well
4. Took several years
   New growth could occur up to 5 times but soon eaten out before final death – threshold occurs suddenly.
5. What is killing the trees? How to treat it? How to manage damaged area?

Group Two observations (west of Berridale):

1. Some pre-dates current occupancy (1973) but has deteriorated since.
2. Most west of Varneys and east of Jindabyne (Manna Gum)
   Also white ant activity esp in last 12 years
   Very little in Jindabyne area (snow gums)
3. Observed new species growing
   Copses have developed, some die others thrive
   Acacias do well
4. –
5. Management options? Fence out? No stock?

Group Three observations (Arable Rd, Bulgundara Rd, Rockwell Rd):

1. 7 years; 5-7 years; 3-5 years
2. Epicormic growth/dead limbs, groups of dead trees
   “Healthy” ➔ leaf loss ➔ epicormic ➔ dead
   Sap bleeding
3. Now trees are dying or dead
4. Gradual change initially and then very rapid
5. Can we do anything with dead trees? What are alternate species? How do we know when a tree is past saving? How can we save trees/costs? Funding available? Is cool burning beneficial? Any option for a parasitic solution? Understory/birds?
Group Four observations (Dalgety):

1. 8-10 years but worst in the last 4-5 years
2. Drought or just after, water stress, springs went dry.
3. Little new growth or regen, wattles took over after fire
   Down by the river, little dieback
   Applebox OK, viminalis the problem (but not everywhere)
   Snowgums OK
4. Becoming treeless hills, eg: Rockwell Road, towards Berridale, OK towards Jindabyne
   Patchy
5. Soil? Granite vs sedimentary vs Basalt, wet vs dry

Known Knowns:

- Patchy
- Episodic
- Species specific
- Insect outbreak
- Fenceline contrasts – there are none
- It has happened

Questions:

- Spread – where is it now and is it spreading?
- Causes
- Management
- Injection
  - Seed trees
  - Priority trees
- Fire
- Reveg/Regen
  - Direct seeding
  - Fire regen
  - Seedlings
  - Grazing exclusion
Appendix 3: Raw data

The raw data collected on the road survey and the site comparisons is located in a separate excel file on the attached DVD (Field Data.xlsx).

Appendix 4: Interactive map of road survey

An interactive map of the road survey containing all the photographs taken at each site is located in a separate file on the attached DVD (Road Survey.kml). Google Earth is required to open this file.
Appendix 5: McElhinny Structural Complexity Index measurement methods

Thirteen structural attributes are measured to calculate the Structural Complexity Index (McElhinny, et al., 2006).

Sampling a patch of vegetation

It is impractical to measure every tree or log in any patch of vegetation. Instead we estimate values for the different attributes by measuring a sample of vegetation. The validity of this approach depends on the selection of an unbiased and representative sample. To ensure this is the case we suggest the following sampling and measurement procedure.

Establish three 50mx20m plots within each patch of vegetation. Estimate each attribute as the mean of the three different estimates obtained from these plots. To capture within patch variation locate plots on a transect running in the direction of the main environmental gradient (assumed to be topography) and passing through the centre of the site. To provide unbiased estimates of site variables distribute the three plots evenly along the site transect starting from a random point 1m-100m from the site edge. Place the long side of the 50mx20m quadrat parallel to the site transect so that proportionately more sampling effort occurs in the direction of the main environmental gradient.

Essential data to be collected at each plot

1. Number of lifeforms (per 400m² plot)

Establish a 20mx20m sub-plot with the main 50mx20m plot. Count the number of different lifeforms occurring in the sub-plot using the following 12 lifeform categories: tussock grass, non-tussock grass, low shrub 0-0.5m, tall shrub>0.5m, sedges / rushes, ferns, vines, xanthorrhoea, mistletoe, overstorey regeneration < 2m, overstorey regeneration > 2m, tree.

Enter your count of lifeforms on the field data sheet.
2. Vegetation cover >0.5m

Establish a 20mx20m sub-plot with the main 50mx20m plot. Divide the 20mx20m plot into four 10mx10m plots. In each 10mx10m plot estimate by eye the horizontal cover of all vegetation that is taller than 0.5m. Include native and non-native vegetation in your estimate. As a guide an area of 1mx1m contributes 1% of horizontal cover to a 10mx10m plot.

Enter your estimates for each of the four 10mx10m plots on the field data sheet.

3. Number of hollow bearing trees

Search the 50mx20m plot and record the total number trees with at least one hollow. Include dead and alive trees in your count of hollow bearing trees. A hollow is a cavity in a stem or branch that can be used by fauna for shelter or nesting. Hollows occur in a range of entrance sizes from less than 1cm to greater than 20cm.

Enter the total number of hollow bearing trees on the field data sheet.

4. Number of trees with a diameter > 40cm

Search the 50x20m plot and record the number of live trees with a diameter >40cm. Measure tree diameter at a point 1.3 m above the ground - this is approximately chest height.

Enter the total number of trees with a diameter > 40cm on the field data sheet.

5. Total length of large logs

Large logs are those with an average diameter greater than 30cm. Search the 50mx20m plot for logs of this size. Record the length of each large log to the nearest 0.5m; estimate the length of the log by eye or by pacing.

Enter the total length of large logs on the field data sheet.

**Additional data which may be collected at each plot**

6. Number of perennial species

Establish a 20mx20m sub-plot with the main 50mx20m plot. Count the number of different perennial species occurring in all lifeforms in the sub-plot.

Enter the total number of perennial species on the field data sheet.

7. Vegetation cover 0-0.5m

Establish a 20mx20m sub-plot with the main 50mx20m plot. Divide the 20mx20m plot into four 10mx10m plots. In each 10mx10m plot estimate by eye the horizontal cover of all vegetation that is less than 0.5m. Include native and non-native vegetation in your estimate. As a guide an area of 1mx1m contributes 1% of horizontal cover to a 10mx10m plot.
Enter your estimates for each of the four 10mx10m plots on the field data sheet.

8. & 9. Basal area of live trees and Quadratic mean diameter

Record the diameter of each live tree occurring in the 50x20m plot using 10cm diameter classes. Measure tree diameter at a point 1.3 m above the ground - this is approximately chest height. Enter each diameter under the appropriate diameter class in the field data sheet.

10. Overstorey regeneration

Search the 50x20m plot and record the total number of regenerating overstorey stems. Regenerating overstorey stems are live stems with a diameter < 5cm belonging to tree species capable of occupying the overstorey canopy. Enter the total number of regenerating stems in the field data sheet.

11. Number of dead trees

Search the 50mx20m plot and count the number of standing dead trees with a diameter > 5cm. Enter the total number of dead trees in the field data sheet.

12. Total length of logs

Search the 50mx20m plot for log with a diameter > 10cm. Record the length of each log to the nearest 0.5m; estimate the length of the log by eye or by pacing

Enter the total length of logs on the field data sheet.

13. Litter dry weight

Take 5 samples of litter at points randomly located within the 50mx20m quadrat. At each point collect all dead organic matter <10cm in diameter within an area of 0.5mx0.5m (0.25m²) – do not include any soil in the litter samples. Place the 5 litter samples in large paper bags and dry in an oven set to 60 °C. Weigh the dried samples and record the total combined weight for the 5 samples in the field data sheet. To accurately estimate litter dry weight it is critical that the litter is properly dried before weighing. Avoid collecting litter after recent rain.
Appendix 6: Crown condition score method

The crown condition score is used to estimate tree health based on visual, ground-based measurements. The total score is the sum of the scores for each of the five attributes; a score out of 25 indicates a vigorous, healthy tree (Stone, et al., 2008).

<table>
<thead>
<tr>
<th>Crown attribute</th>
<th>Score</th>
<th>Brief description</th>
<th>Expanded description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown size and shape</td>
<td></td>
<td></td>
<td>overall degree of crown dieback, comparing present extent of living foliage compared to the estimated amount that would have been presented by the original, unaffected crown</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Large, vigorous</td>
<td>Well-balanced, fully-extended crown, shaped by large branches containing a healthy ‘hierarchy’ of smaller branches supporting foliage</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Moderate</td>
<td>Moderately-contracted crown, non-uniform in shape with foliage unevenly distributed. Approximately half of the outer, smaller branches dead or missing</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Contracted</td>
<td>Crown contracted, all outer branches dead or missing, foliage on only major branches or stem arising from epicormic growth</td>
</tr>
<tr>
<td>Crown foliar density</td>
<td></td>
<td></td>
<td>inverse to crown transparency</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Very dense</td>
<td>Very dense leaf clumps with even distribution of clumps over the crown. Very little light penetrating the leaf clumps</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Dense</td>
<td>Dense leaf clumps distributed unevenly over the crown</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Moderate</td>
<td>Clumps of average density with reasonable distribution or dense clumps very unevenly spread</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Sparse</td>
<td>Clumps are sparse and poorly spread</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Very Sparse</td>
<td>Very few leaves anywhere in crown</td>
</tr>
<tr>
<td>Dead branches</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Nil</td>
<td>No visible dead branches or branchlets/shoots in the crown</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Dead terminal shoots</td>
<td>On close inspection some dead terminal branches are evident but not over all the crown</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Dead small branches</td>
<td>Some small branches are dead but not over all the crown. These are easily observed but do not give the impression of seriously affecting the crown</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Dead main branches</td>
<td>Some large and or small branches dead over part of the crown with the obvious impression of serious branch death</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Dead main branches</td>
<td>Large and small branches dead over most of the crown which is obviously dying</td>
</tr>
<tr>
<td>Crown epicormic growth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Nil</td>
<td>Limbs clean, growth concentrated at branch extremities</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Moderate</td>
<td>Moderate amount of epicormic growth is present over most of the crown but foliage from primary shoots still present</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Severe</td>
<td>Epicormic growth is dominant source of foliage over most of the crown</td>
</tr>
<tr>
<td>Foliar damage</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Low</td>
<td>No insect or fungal damage visible in the crown from the ground, no reddish-purple or brown discoloration present or only a small amount on old foliage</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Moderate</td>
<td>Obvious reddish-purple or brown discoloration on some of the foliage, insect or fungal damage may be visible from the ground</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>High</td>
<td>Insect or fungal damage severe enough to be visible from the ground, foliage may have a ‘tatty’ appearance. Crown has an overall reddish-purple or brown coloration.</td>
</tr>
</tbody>
</table>
Appendix 7: Dieback fact sheet for Greening Australia

This fact sheet was developed for Greening Australia staff and stakeholders, and intended to provide some basic information and management strategies. It is not aimed specifically for the Monaro region but for dieback in general, and many of the management strategies suggested are unlikely to be successful in the Monaro case.

Fact Sheet
Dieback in south-east Australia

What is dieback?

Dieback is a general term describing a widespread long-term decline in tree health. It may be caused by a range of factors but has widely recognisable symptoms.

The first sign of dieback is usually canopy thinning which starts at the branch tips, followed by defoliation, epocormic growth (from the trunk and branches), and dead branches, eventually leading to tree death.

Causes of dieback

Dieback may be caused by a range of interacting factors, making it very difficult to predict or treat. Some suggested causes include agricultural practices (grazing, improved pastures, fertilisation, clearing), altered fire regimes, and climatic effects (warming, extreme events e.g. flood, drought). It is often associated with insect outbreaks.

Although insect outbreaks are a natural occurrence, under certain conditions they can cause significant damage. As defoliated trees begin to recover, they produce epocormic growth which is very palatable to insects. This creates a feedback effect where trees are defoliated repeatedly over several years until they exhaust their energy reserves and eventually die.

Underlying factors contributing to insect related dieback may include:

- **Tree stress** – disease, weather, physical damage, soil, mistletoe etc.
- **Increased nutrient content of leaves** – fertilisation, build-up of manure, improved pastures
- **Favourable weather conditions** – depends on the type of insect. For example, Christmas Beetles mature in the soil so they benefit from high soil moisture in wetter seasons
- **Isolation** – lack of habitat for natural predators, exposure, greater insect burden on each tree
Dieback - Management and prevention

What can you do?

- Don't cut down affected trees – they are very resilient and may still recover.
- Stem injected pesticides – imidacloprid (Bayer Silvashield for tree injection). Effective for small numbers of trees in the short term (4 years), but very expensive and labour intensive at large scales.
- Avoid physical damage to trees – limit ploughing and herbicide application around remnant trees.
- Fence trees to exclude stock where possible - to allow regeneration and prevent ringbarking, compaction of soil and build-up of manure.
- Replant diverse native species and retain native pastures to attract native insectivorous birds and mammals and beneficial insects. For example, *Bursaria spinosa* is a flowering shrub that is vital habitat for a parasitic wasp that helps to control Christmas beetles.
- Aim to connect isolated trees with other remnant vegetation using corridors; or replant large areas around isolated trees.

Insect-related dieback near Berridale, NSW – Photo: Tim the Yowie Man

**Greening Australia** can provide funding and advice for projects that improve ecosystem function and provide benefits for production.

Call 02 62533035 for more information.

March 2013