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Summary

Over the last decade, substantial numbers of *Eucalyptus viminalis* across the Monaro plains in south-eastern NSW have been observed as declining in health. Based on a systematic road survey, the affected area is estimated to cover around 2000 km^2, with almost all *E. viminalis* within that area either dead or severely affected. Other eucalypt species present show minor levels of health deterioration. Field observations include widespread infestation of an endemic but previously undescribed species of eucalyptus weevil (*Gonipterus* sp.). Eight sites were chosen to represent the range of management practices and recent fire history in the affected area. The structural complexity, tree health and level of weevil infestation were determined at each site, and despite large differences in structural elements and overall complexity, the severity of dieback was consistently severe across the range. There does not appear to be sufficient evidence to conclude that changed land management practices, recent fire history or declining levels of structural complexity are responsible for this 'Monaro dieback'. If the dieback continues at the current rate, it seems inevitable that *E. viminalis* will disappear entirely from the Monaro region. As *E. viminalis* is the dominant species in most of the region, such disappearance will have very serious consequences on the ecology of the region. Further work is required to determine if the dieback is related to changes in climate or rainfall patterns. Trials of potential replacement *E. viminalis* genotypes and alternative eucalypt species should be undertaken as a precaution in case the dieback cannot be reversed.

Keywords: dieback; structural complexity; *Eucalyptus viminalis*; *Gonipterus* sp; Monaro

Introduction

Eucalypt dieback, characterised by a gradual deterioration in tree health over months or years and eventually leading to premature death, has been reported for all states in Australia (e.g. over the past decade, Rice *et al*. 2004; Calder and Kirkpatrick 2008; Stone *et al*. 2008; Close *et al*. 2009; Evans *et al*. 2013). Recently, the health of eucalypts on the rolling grassy plains and rocky outcrops of the Monaro region of south-eastern NSW appears to have substantially declined and many are now dead (Fig. 1).

Dieback is often referred to as a 'disease of complex aetiology', caused by a combination of biotic and abiotic factors including exotic or native organisms, pollution, land management practices, climatic change or extremes, or natural succession (Manion 1981; Old 2000). While dieback may be caused by a range of interacting factors, it is commonly associated with insect attack. Often, however, insect attacks are a secondary or contributing factor that occurs as a result of other underlying issues such as tree stress, nutrient imbalances or climate (Manion 1981).

In Australia, several episodes of insect-related eucalypt dieback have been attributed to agricultural practices, which lead to degradation and simplification of ecosystems (Landsberg and Wylie 1988; Close 2003; Doyle 2005; Davidson *et al*. 2007). This is known as 'rural dieback', and may be the result of one or more of the following:

- Isolation and exposure of individual trees
- Loss of habitat for insect predators or parasites
- Soil degradation and compaction
- Fertilisation and pasture improvement
- Competition (pasture, weeds, mistletoe, etc.)
- Pollution or herbicides
- Climatic factors

Insect outbreaks lead to defoliation of the canopy, to which the tree responds by producing epicormic foliage (Ohmart and Edwards 1991). However, epicormic growth tends to be more palatable and nutritious to insects, so this can trigger a feedback loop in which the trees are repeatedly defoliated until they eventually succumb to carbohydrate depletion (Mackay *et al*. 1984; Landsberg 1990a, 1990b).

Fire also plays a very important role in eucalypt ecosystems, and the exclusion of fire can cause a range of changes such as promoting the development of a dense understorey, changed soil conditions and nutrient imbalances (Ellis *et al*. 1980; Lunt 1998; Jurskis and Turner 2002; Jurskis 2005a, 2005b; Turner *et al*. 2008; Close *et al*. 2009, 2011). These changes may place trees under stress and create conditions that are beneficial to herbivorous insects.

Climate and extreme weather events have also been linked to dieback events (Pook and Forrester 1984; Landsberg 1985; Auclair 1993; Close and Davidson 2004; Allen 2009; Allen *et al*. 2010; Evans *et al*. 2013), either through direct effects on trees (e.g. water stress may make trees more susceptible to

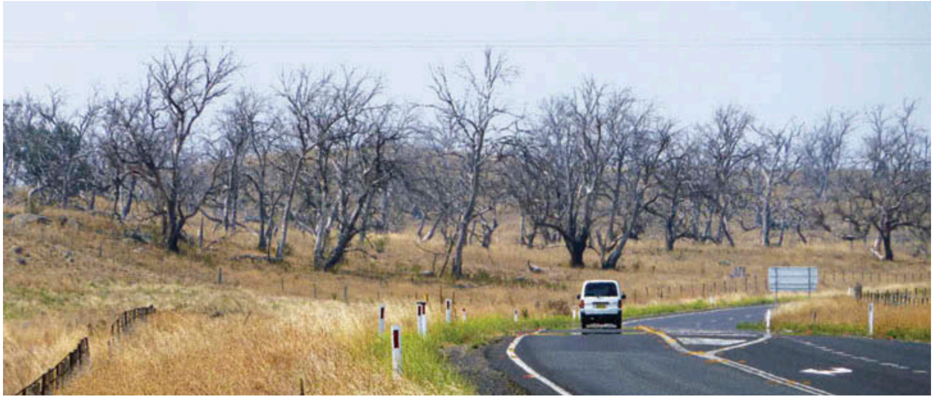

Figure 1. *Eucalyptus viminalis* dieback on Jindabyne Road between Cooma and Berridale. Photo: Tim the Yowie Man

insect attack—White 1969, 1986; Landsberg and Wylie 1983; Landsberg and Cork 1997; Huberty and Denno 2004) or by affecting the insects themselves (e.g. higher temperatures may increase growth and reproduction rates—Stange and Ayres 2010). Some studies have also shown that stress causes a reduction in foliar nutritional quality, and suggest that certain insects prefer the foliage of trees growing in benign conditions (Landsberg 1990c; Price 1991).

The Monaro region of south-eastern NSW is one of Australia's iconic ecosystems, and the loss of the remaining trees in this landscape could have very serious consequences both ecologically and economically. However, the dieback in this region has received very little attention in the scientific literature.

In this study, we determine the extent and severity of what we term the 'Monaro Dieback'. Further, we report a preliminary attempt to isolate the potential causal agents of the dieback. Previous observations of large numbers of a species of eucalyptus weevil belonging to the *Gonipterus* genus suggest that an outbreak of insect predation is associated with the dieback (Murdoch, University of Sydney, personal communication, 2012; personal observation). We therefore examine the presence of *Gonipterus* sp. across a range of management practices and fire histories to determine if there is any relationship between management, infestation and severity of the dieback.

If the dieback in the Monaro is the result of increases in insect populations due to agricultural practices or changes to the recent fire history, the severity of dieback should be related to structural attributes that have been shown to contribute to the complexity and diversity of the ecosystem. Trees in relatively undisturbed and more complex sites would be expected to have increased resilience and hence be in better health than those on agricultural land and where fire has been excluded.

Methods

Study area

The Monaro region is a plateau in the highlands of south-eastern NSW (elevation 700–1100 m), between the ACT and the Victorian border, with the Snowy Mountains to the west and the coastal escarpment to the east. Due to the low rainfall (500–700 mm annually), severe frosts and poorly aerated soil much of the Monaro region is naturally treeless (Costin 1954; Jenkins and Morand 2002). However, small pockets of temperate savannah woodland occur on rocky outcrops, with heavier forested areas on isolated hilltops, ranges and in river valleys (Taylor and Roach 2003). The dominant overstorey species in the region is *Eucalyptus viminalis*, which may co-occur with other species such as *E. rubida, E. pauciflora* and *E. stellulata*. The region has historically been used for grazing and has been cleared and sown with exotic pasture grasses, but scattered trees remain and some areas of relatively undisturbed vegetation exist in state and travelling stock reserves.

Due to the gradual nature of deterioration, it is difficult to pinpoint when dieback began. Anecdotal evidence suggests that the Berridale travelling stock reserve (TSR) (Fig. 2) was one of the first locations where dieback was observed in about 2005 (Murdoch, University of Sydney, 2012, personal communication). This period coincides with an extended drought in the region, but similar periods of extended below-average rainfall have previously occurred (e.g. 1926–1931; 1937–1946) without being associated with reports of dieback (Fig. 3).

The study area lies well within the historic geographic range of *E. viminalis*, although it does appear to exist in one of the drier parts of that distribution (Fig. 4).

Determining the extent of the Monaro dieback

Preliminary surveys indicated that the dieback was largely restricted to *E. viminalis* and apparent boundaries or patterns in dieback severity were actually due to species changes. It was determined therefore that remote-sensing-based approaches to mapping the dieback would have extensive problems with false negatives due to the difficulties in identification of similar-looking tree species. A ground-based transect survey was impractical due to large numbers of absentee landowners and the difficulty of getting permission to access private land. A road survey therefore was carried out to determine the extent, severity, symptoms and patterns of the Monaro dieback.

In January 2013, a survey systematically traversed all the main roads and some secondary roads across the affected area, stopping at 5 km intervals along the route. At each stop, two photographs were taken to the left and right of the road. The overstorey species present, the severity of dieback on a scale

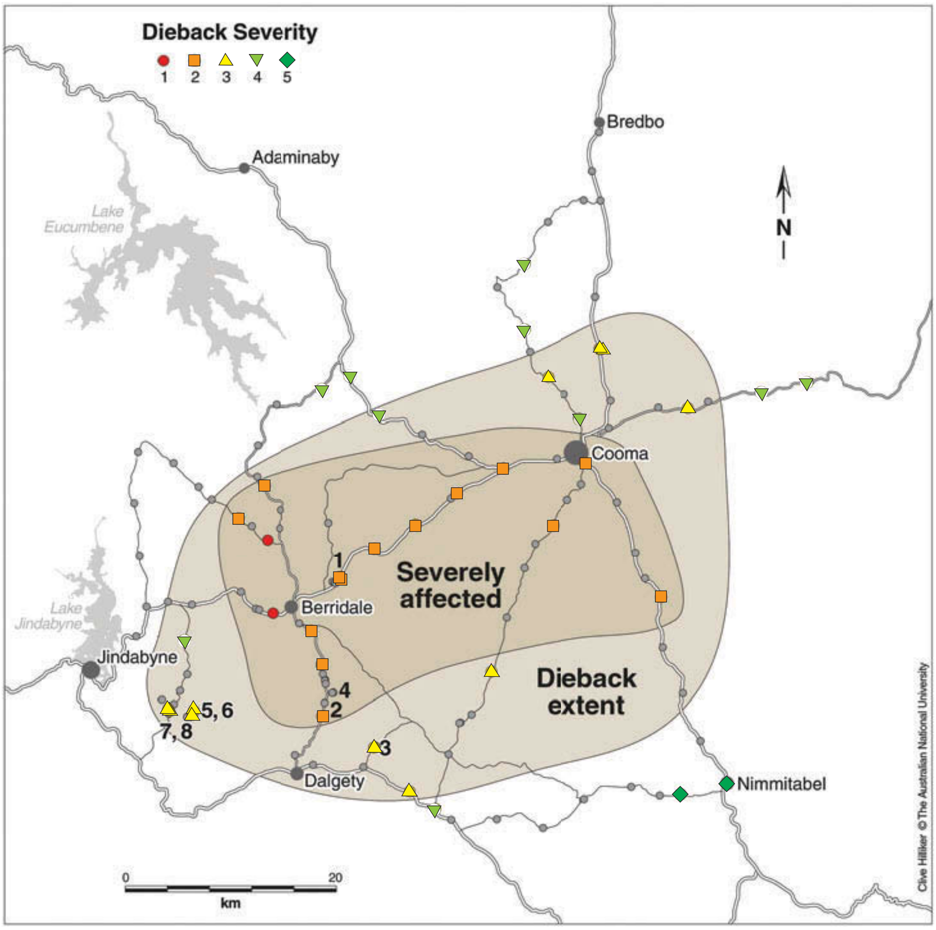

Figure 2. Map of Monaro region showing road survey sites (grey circles indicate no *E. viminalis* present, coloured circles indicating dieback severity), study sites (labelled 1–8), and dieback extent (outer shaded area) and severely affected area (inner shaded area)

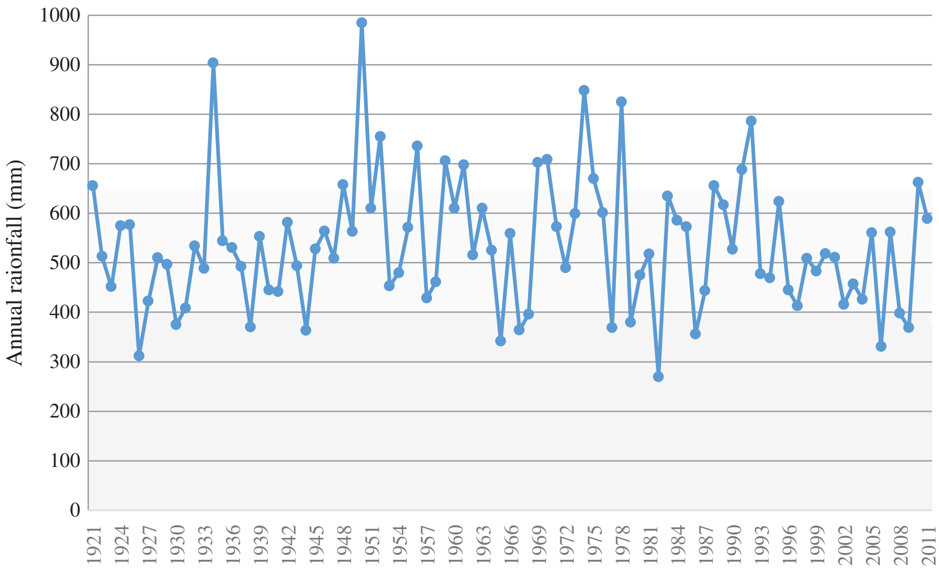

Figure 3. Annual rainfall for the Monaro region (Berridale TSR, Site 1) as interpolated from Bureau of Meteorology weather stations using the ANUSPLIN software (Hutchinson 2004)

from 1 to 5 (1 being completed dead, 5 being healthy), 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 (hilltop, slope, flat) were recorded at each stop. Observations were recorded as far as was visible in any direction (up to about 2 km). The survey was extended 10–15 km beyond the edge of the affected area

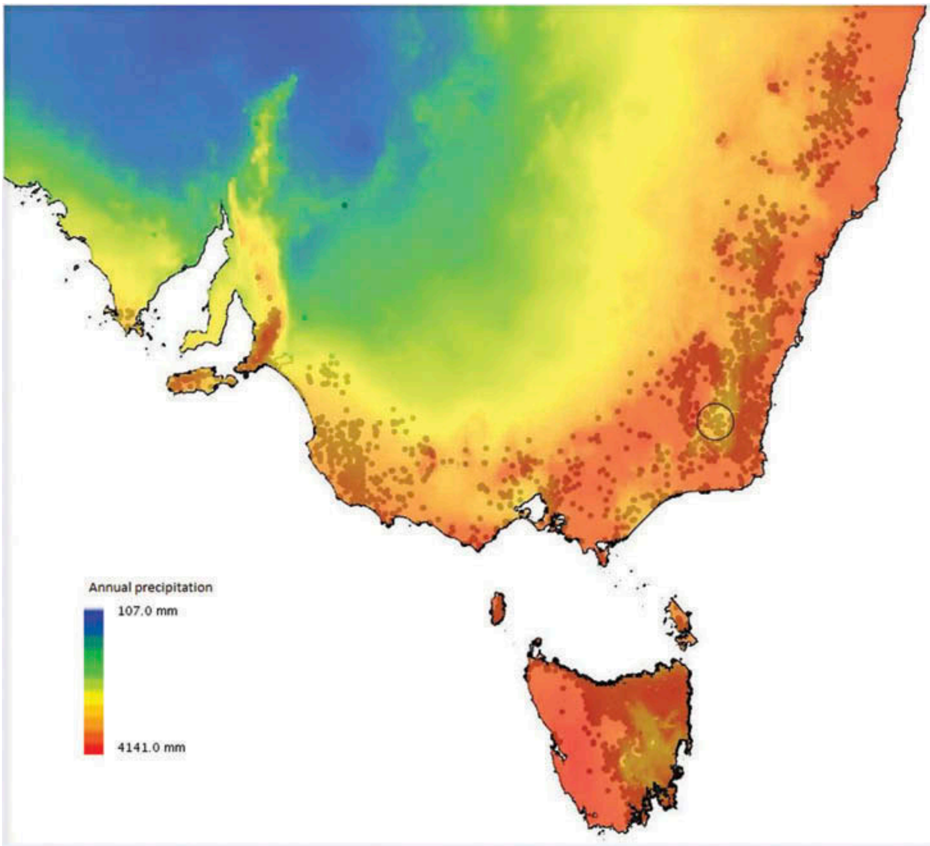

Figure 4. *E. viminalis* distribution vs. annual precipitation. Dots are locations where *E. viminalis* has been recorded. The Monaro region is circled, and is clearly much drier than the surrounding region. *E. viminalis* distribution is strongly related to moisture. (Map created using the *Atlas of Living Australia*, http://www.ala.org.au/)

(where affected trees were no longer evident) to ensure the full extent of the dieback area was included.

Visual evidence of the presence of eucalyptus weevils (adults, larvae, eggs or feeding damage) was collected at stops on the road survey where trees with any remaining foliage were accessible.

Severity of dieback—site comparisons

Eight sites were selected for study from the mapped dieback area (Fig. 2). These sites systematically covered the range of management, disturbance and recent fire (Table 1). Again, due to access issues, sampling was restricted to properties where the landowners expressed a willingness to be included. Pairs of sites were selected with each of the pair representing a substantial difference in either management or disturbance. For example, TSRs near Berridale and Dalgety, which were relatively undisturbed, with no evidence of heavy grazing, pasture improvement or burning, were paired with a site that was used regularly for sheep grazing and had also not been pasture-improved or burnt. A second grazed site was chosen on a private property neighbouring site 2, but the landowner subsequently refused access (for unknown reasons) so detailed measurements could not be taken, although simple observations were made. For another pair near Barneys Range, one property was partially burnt in 2003, providing an excellent comparison between adjacent burnt and unburnt sites.

At each site, an estimate of dieback severity was made for the trees and the structural attributes for the stand were assessed using the McElhinny Structural Complexity Index (SCI). The SCI measures 13 structural attributes of a forest or woodland and compares these with equivalent sites to give an overall score for stand complexity. 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. The methods for measuring each attribute are taken from McElhinny *et al*. (2006).

To calculate the SCI, the site is compared with either woodland or forest reference sites, to account for innate structural differences between these vegetation types. For this 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 SCI, this site was not included in the analysis but was useful as observational data.

The method described in Stone *et al*. (2008) was used to estimate the severity of dieback for each tree within the plots

Table 1. Site description

Attribute	Site number 1	2	3*	4	5*,†^	6*,†	7*,†	8*,†
Site name	TSR Berridale	TSR Dutton	Rudd	Sunnyside	O'Brien1	O'Brien2	Dickson1	Dickson2
Grazed/ungrazed	Ungrazed	Ungrazed	Grazed	Grazed	Ungrazed	Ungrazed	Ungrazed	Ungrazed
Burnt/unburnt	Unburnt	Unburnt	Unburnt	Unburnt	Unburnt	Burnt	Burnt	Burnt
Forest/woodland/paddock	Woodland	Woodland	Woodland	Woodland	Forest	Forest	Forest	Paddock
Improved?	Not improved	Not improved	Not improved	Improved	Not improved	Not improved	Not improved	Improved
Elevation (approx., m)	900	900	900	900	850	850	1000	1000
Aspect	SE	SE	SE	SE	SE	SE	S	S
Mean annual rainfall (mm)	536	536	593	536	567	567	567	567
Mean annual temperature (°C)	11.3	11.2	10.4	11.2	11.2	11.2	11.2	11.2
Dominant overstorey species	*E. viminalis*	*E. viminalis*	*E. viminalis*	*E. viminalis*	*E. viminalis*	*E. viminalis*	*E. viminalis/ E. pauciflora*	*E. viminalis*
Other overstorey species	*E. rubida, E. pauciflora*	*E. rubida*	*E. bridgesiana, A. implexa*	*E. rubida, E. bridgesiana*	*E. rubida, E. pauciflora*	*E. rubida, E. pauciflora*	*E. rubida, E. pauciflora, E. stellulata*	n/a
Midstorey	*Acacia* sp., briar	*Acacia* sp., *Bursaria* sp. etc.	*Acacia* sp.	briar	*Acacia* sp., *Cassinia* sp. etc.	*Acacia* sp.	*Acacia* sp.	*Acacia* sp.

*Dieback noted in last 2 years.
†Burnt in 2003.

established for the SCI. 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.

Results

Monaro dieback—extent, severity, symptoms, patterns

The road survey covered around 400 km of roads in the Monaro region between Bredbo, Numeralla, Nimmitabel and Jindabyne, with 75 stops at 5 km intervals. At 34 of those stops (45%), *Eucalyptus viminalis* were present, with 26 of those (76%) showing clear signs of dieback.

The Monaro dieback covers a total geographic area of around 2000 km^2 (Fig. 2). There seems to be a central area between Berridale and Dalgety that is severely affected (tree crown score 1–2) and an outer less affected area (tree crown score 3–4). The edges of the affected area appear to be gradual, defined by changes in species composition from communities dominated by *E. viminalis* to other communities.

Eucalyptus viminalis is the dominant overstorey species in the affected area, and is consistently the worst affected. Other eucalypt species such as *E. rubida, E. bridgesiana, E. pauciflora, E. stellulata* and some acacias such as *Acacia implexa* and *A. mearnsii* occur in small patches or scattered amongst stands of *E. viminalis*, but are less affected and often stand out as the only healthy trees remaining.

At every accessible location along the road survey, weevil adults and larvae were found in large numbers, along with egg cases. All affected trees showed characteristic feeding damage caused by both adult weevils and larvae.

The weevil found to be involved with the Monaro dieback was identified by Dr Oberprieler at CSIRO as a previously undescribed species known as *Gonipterus* sp. *no. 2* (Oberprieler, CSIRO, personal communication, 2012), part of a complex of ten cryptic species previously known as *G. scutellatus* (Mapondera *et al.* 2012). This weevil is native to the region but has become a serious pest when introduced to eucalypt plantations overseas (Tooke 1953; Rivera *et al.* 1999; Hanks *et al.* 2000).

Site comparisons

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 2). The lowest scoring (least healthy) 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* (Fig. 5). 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 (Fig. 6). 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.

Table 2. Crown health score

	Site number							
Attribute	1	2	3	4	5	6	7	8
Crown size/ shape (/5)	0.93	1.38	2.21		2.33	1.86	3.44	2.75
Foliar density (/5)	0.98	1.43	2.08		2.35	1.79	3.41	2.65
Dead branches (/5)	0.86	1.48	2.19		2.22	1.66	3.32	2.76
Epicormic growth (/5)	1.12	1.71	1.87		2.50	2.07	4.02	4.12
Foliar damage (/5)	0.88	1.19	2.00		2.08	1.64	2.86	2.51
Total (all trees)	4.76	7.19	10.35	4*	11.48	9.01	17.04	14.79
Total (adult *E. viminalis* only)	0.72	1.15	8.65	1*	9.87	6.55	7.61	12.75

*Estimates based on occular measurement and photographs.

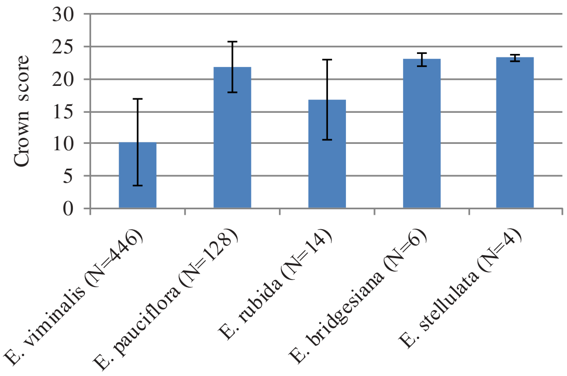

Figure 5. Tree health—species

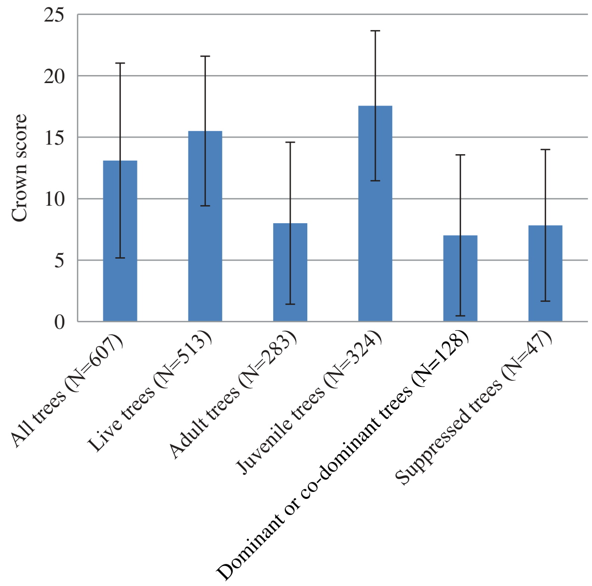

Figure 6. Tree health by categories

Table 3. Structural Complexity Index
(a) Quantitative version

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

*No quantitative data available; qualitative estimates based on ocular measurements and photographs, and not included in calculations of correlations etc.

(b) Qualitative version

Attribute	Site number							
	1	2	3	4*	5	6	7	8
Number of perennial species (species/ plot)	Average	Average	Poor	Average	Poor	Average	**Good**	Average
Number of lifeforms (lifeforms/plot)	Average	Average	Average	Average	Average	**Good**	Poor	Poor
Basal area of live trees per unit area	Poor	Poor	Poor	Poor	Poor	Poor	Poor	**Good**
Quadratic mean dbh	Poor	Poor	Poor	Poor	**Good**	Average	Poor	Average
0–0.5 m vegetative cover (%)	**Good**	**Very high**	**Good**	**Good**	**Very high**	**Very high**	**Very high**	**Very high**
0.5–6.0 m vegetative cover (%)	**Very high**	**Very high**	**Very high**	**Good**	**Very high**	**Very high**	**Very high**	**Good**
Overstorey regeneration (stems/unit area)	Poor	Poor	Poor	Poor	Poor	Poor	**Good**	Average
Hollow-bearing trees (stems/unit area)	Average	**Good**	Average	Average	Average	**Good**	Poor	**Good**
Trees with dbh > 40 cm (stems/unit area)	Average	Average	Average	Average	**Good**	Average	Poor	Average
Dead trees (stems/unit area)	**Very high**	**Good**	**Good**	**Good**	Poor	Average	Average	**Good**
Length of logs (> 10 cm diameter) (length/unit area)	**Good**	**Good**	**Very high**	**Good**	**Very high**	**Very high**	Average	Average
Length of large (> 30 cm diameter) logs (length/unit area)	**Very high**	**Very high**	**Very high**	**Good**	**Very high**	**Very high**	Average	Poor
Litter dry weight (mass/unit area)	Poor	Poor	Poor	Poor	Poor	Poor	Poor	Poor
Structural complexity index score	61	64	62	61*	61	62	54	64
Percentile ranking	70.6	76.5	76.5	70.6*	48.5	54.5	33.3	76.5

*Estimates based on ocular measurements and photographs, and not included in calculations of correlations etc.

The SCI scores ranged from 54 to 64 when compared with appropriate reference sites (woodland or forest) (Table 3). Scores for all attributes were quite variable across sites, which was expected given the range of management and disturbance history sampled. 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 table indicates whether the site was poor, average, good or very high (outside the reference range) for that attribute, as compared to the reference sites.

All sites scored high to very high for ground (< 0.5) and midstorey (0.5–6 m) cover, but the measurements were taken in spring after several wet years (Fig. 4, 2010–2011). Sites that were burnt in 2003 appear to have stimulated regeneration, particularly of *Acacia* species. This was particularly apparent at site 6 which was dominated by *Acacia* and had a mid-storey density almost double that of the neighbouring unburnt area (site 5).

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.

Regeneration was scant 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 (Fig. 6), so it is unlikely that the low regeneration scores at other sites were a direct result of dieback. Adult trees affected by dieback, however, have been shown to have reduced reproductive capacity (Landsberg 1988; Landsberg *et al*. 1990) and the Monaro is also a notoriously difficult environment for tree seedlings to establish.

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). There was, however, a significant positive correlation between the crown scores and basal area (r = 0.95, P < 0.05), and quadratic mean diameter (r = 0.7, P < 0.05), and a significant negative correlation between crown health and the number of dead trees (r = –0.7, P < 0.05).

Discussion

The road survey was able to give a consistent and reliable indication of the extent, severity and spatial patterns of the Monaro dieback. This survey found that by 2013 Monaro dieback currently covered a huge area—almost the size of the Australian Capital Territory at 2000 km^2. The size of the problem should cause concern as this area is now almost entirely devoid of living *E. viminalis*, which were once the dominant species in the area. This represents a huge loss in terms of production, biodiversity and aesthetics.

Anecdotally, there have been reports of clear boundaries where dieback suddenly stops (Freudenberger, ANU, personal communication, 2012). 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. The change in plant communities is likely to be caused by a range of factors including climate and soil type.

The importance of the eucalyptus weevil in this dieback is demonstrated by the fact that all affected trees showed feeding damage caused by both adult weevils and larvae, and that *E. viminalis* is known to be a preferred host (Phillips 1992; Elliott *et al*. 1998; Newete *et al*. 2011).

Given that the weevil is a native species and has not been known to have outbreaks in Australia before, there must be an underlying cause for this unusual event. The eucalyptus weevil is a specialist flush feeder, preferring new flushing foliage for both adults and larvae, and for oviposition sites (Matsuki and Tovar 2010; personal observation). Usually, competition for limited resources, along with parasitism and predation, maintain consistently low population levels. 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 (Price *et al*. 1990; Landsberg and Cork 1997).

In other studies of rural dieback, healthy trees were often found neighbouring those affected by dieback (e.g. Landsberg and Wylie 1983). This allows a clear comparison between healthy and declining trees within a small area, eliminating many of the potential explanations for the dieback. This was not the case in our study as 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.

Despite the wide range of land management practices, the severity of dieback remained consistently high, which suggests that land management has little effect on dieback severity. Unlike other episodes of dieback where grazing land was more affected by dieback than ungrazed 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 withdrew) 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.

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 with only scattered large trees and thickets of regrowth around 10 years old or younger. The tree vigour theory would predict that trees growing in highly fertile soil should have foliage of higher dietary quality for insects, and thus be more likely to be severely affected by insect-related dieback. However, if moisture had been generally limiting over the entire region, this locally wet site might have reduced the tree stress sufficiently to reduce the impact of dieback.

Clearing leading to isolation, exposure and a lack of habitat for important predators or parasites has often been thought to contribute to dieback in rural areas. However, in this case, all sites scored relatively highly for understorey cover and dieback severity was not greatly different across sites with different understorey densities (Fig. 7). The presence of dieback in forested areas that have not experienced clearing would also seem to be counter to the expectations of the isolation theory.

Comparison of neighbouring sites 5 (unburnt) and 6 (burnt) demonstrates some differences between sites affected by the fire of 2003 (Fig. 8). The burnt site had a lower crown score, but this was largely due to a greater 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 time. There was no difference in the severity of dieback in the living trees. While fire exclusion has been shown to lead to understorey proliferation, which may affect insect habitat and predation, the fire in this case stimulated thick regeneration of acacias and greater incidence of overstorey regeneration.

Although all the sample sites had SCI scores over 50 and all except one (site 7) scored above average complexity compared

Figure 7. 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

Figure 8. 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

with the reference sites, every site had quite severe dieback. The lack of any significant pattern with SCI and severity of dieback does not support the hypothesis that sites with greater structural complexity are more resilient to dieback in the Monaro.

It is possible that the effects of dieback on structural complexity attributes over the past decade might be affecting the calculation of SCI and masking evidence of any original cause or inherent resilience. For example, dieback would be expected to increase numbers of dead trees, and as such, basal area and quadratic mean diameter of living trees 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 but create less fine 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). Similarly, the loss of canopy cover due to dieback allows more light to the ground and there might be less competition for water with the declining overstorey and consequently high to very high ground storey (< 0.5 m) and mid-storey (0.5–6 m) cover. Because the SCI is a measurement at a single point in time, it is impossible to tell whether dynamic attributes like the understorey density is a contributing factor or a symptom of the dieback.

The lack of small-scale variation or any obvious effects of management or disturbance in the severity of dieback suggests the need to look for larger-scale causes. A climatic cause is consistent with such a scale and the apparent onset of the Monaro dieback appears to have coincided with one of the worst droughts on record, during which rainfall was well below average (Murphy and Timbal 2008; CSIRO 2010). In addition, the dieback has occurred in an area that was already particularly dry in comparison to the rest of the range of *E. viminalis*, and is on the edge of the species' range in terms of annual rainfall (Florabank 2013). Further research is being undertaken to investigate changes in rainfall and temperature patterns and the underlying mechanism linking climate with dieback.

If the dieback continues at the current rate, it seems inevitable that *E. viminalis* will disappear entirely from the Monaro region. As *E. viminalis* is the dominant species in most of the region, this will have very serious consequences. The lack of any relationship between dieback severity and differences in land use or fire history suggests that current management practices aimed at increasing structural complexity are unlikely to be effective. These actions should not be abandoned, however, and trials of potential replacement species should be undertaken.

Conclusions

By 2013, the Monaro dieback has severely affected an area of about 2000 km^2 in the highland plateau of south-eastern NSW.

Like many cases of dieback, the immediate cause of tree decline is repeated defoliation by an insect, in this case the eucalyptus weevil (*Gonipterus* sp.). The dieback is specific to *E. viminalis*, the preferred host of the eucalyptus weevil, and the edges of the dieback are defined by changes in composition of the tree flora. Within the affected area, all *E. viminalis* are severely affected and there is little small-scale variation in the severity of dieback. Despite large differences in structural elements and overall complexity, there was little difference in the severity of dieback (consistently severe), suggesting that high structural complexity did not increase resilience to dieback. Similarly, the severity remained consistently high despite wide variations in land management and disturbance. The most likely explanation for the Monaro dieback seems to be larger in scale than local management actions or disturbances previously associated with many examples of rural dieback.

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References

Allen, C. (2009) Climate induced forest dieback—an escalating global problem? *Unasylva* **60**, 43–49.

Allen, C., Macalady, A., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D., Hogg, E., Gonzalez, P., Fensham, R., Zhangm, Z., Castro, J., Demidova, N., Lim, J., Allard, G., Running, S., Semerci, A. and Cobb, N. (2010) A global overview of drought and heat-induced mortality reveals emerging climate change risk for forests. *Forest Ecology and Management* **259**, 660–684. doi:10.1016/j.foreco.2009.09.001

Auclair, A. (1993) Extreme climatic fluctuations as a cause of forest dieback in the Pacific rim. *Water, Air and Soil Pollution* **66**, 207–229.

Calder, J.A. and Kirkpatrick, J.B. (2008) Climate change and other factors influencing the decline of the Tasmanian cider gum (*Eucalyptus gunnii*). *Australian Journal of Botany* **56**, 684–692. doi:10.1071/BT08105

Close, D. (2003) Rural tree decline in Tasmania: a complex of factors. *The Tasmanian Naturalist* **125**, 27–31.

Close, D. and Davidson, N. (2004) Review of rural tree decline in a changing Australian climate. *Tasforests* **15**, 1–18.

Close, D., Davidson, N., Johnson, D., Abrams, M., Hart, S., Lunt, I., Archibald, R., Horton, B. and Adams, M. (2009) Premature decline of *Eucalyptus* and altered ecosystem processes in the absence of fire in some Australian forests. *Botanical Review* **75**, 191–202. doi:10.1007/s12229-009-9027-y

Close, D., Davidson, N. and Swanborough, N. (2011) Fire history and understorey vegetation: water and nutrient relations of *Eucalyptus gomphocephala* and *E. delegatensis* overstorey trees. *Forest Ecology and Management* **262**, 208–214. doi:10.1016/j.foreco.2011.03.025

Costin, A. (1954) *A Study of the Ecosystems of the Monaro Region*. A. H. Pettifer, Government Printer, Sydney.

CSIRO (2010) Climate variability and change in south-eastern Australia: a synthesis of findings from Phase 1 of the South Eastern Australian Climate Initiative (SEACI). 36 pp. Accessed 31 July 2015. Available from http://www.seaci.org/publications/documents/SEACI-1%20Reports/Phase1_SynthesisReport.pdf

Davidson, N.J., Close, D.C., Battaglia, M., Churchill, K., Ottenschlaeger, M., Watson, T. and Bruce, J. (2007) Eucalypt health and agricultural land management within bushland remnants in the Midlands of Tasmania, Australia. *Biological Conservation* **139**, 439–446. doi:10.1016/j.biocon.2007.07.019

Doyle, R. (2005) *Soil and Hydrological Factors Affecting Rural Tree Decline in the Midlands of Tasmania*. National Heritage Trust Project Final Report School of Agricultural Sciences, University of Tasmania, Hobart.

Elliott, H., Ohmart, C. and Wylie, F. (1998) *Insect Pests of Australian Forests: Ecology and Management*, Inkata Press, Melbourne, 214pp.

Ellis, R., Mount, A. and Mattay, J. (1980) Recovery of *Eucalyptus delegatensis* from high altitude dieback after felling and burning the understorey. *Australian Forestry* **43**, 29–35. doi:10.1080/00049158.1980.10674242

Evans, B., Stone, C. and Barber, P. (2013) Linking a decade of forest decline in the south-west of Western Australia to bioclimatic change. *Australian Forestry* **76**, 164–172. doi:10.1080/00049158.2013.844055

Florabank (2013) *Fact Sheet—Eucalyptus viminalis*. Accessed 31 July 2015. Available from http://www.florabank.org.au/lucid/key/species%20navigator/media/html/Eucalyptus_viminalis.htm

Hanks, L., Millar, J., Paine, T. and Campbell, C. (2000) Classical biological control of the Australian weevil *Gonipterus scutellatus* (Coleoptera: Curculionidae) in California. *Environmental Entomology* **29**, 369–375. doi:10.1093/ee/29.2.369

Huberty, A. and Denno, R. (2004) Plant water stress and its consequences for herbivorous insects: a new synthesis. *Ecology* **85**, 1383–1398. doi:10.1890/03-0352

Hutchinson, M. (2004) ANUSPLIN Version 4.3. Fenner School of Environment and Society, Australian National University. Accessed 31 July 2015. Available from http://fennerschool.anu.edu.au/research/products/anusplin

Jenkins, B. and Morand, D. (2002) A comparison of basaltic soils and associated vegetation patterns in contrasting climatic environments. In: Roach, I.C. (ed.) *Regolith and Landscapes in Eastern Australia*. CRC LEME, Bentley, WA, pp. 76–80.

Jurskis, V. (2005a) Eucalypt decline in Australia, and a general concept of tree decline and dieback. *Forest Ecology and Management* **215**, 1–20. doi:10.1016/j.foreco.2005.04.026

Jurskis, V. (2005b) Decline of eucalypt forests as a consequence of unnatural fire regimes. *Australian Forestry* **68**, 257–262. doi:10.1080/00049158.2005.10674974

Jurskis, V. and Turner, J. (2002) Eucalypt dieback in eastern Australia: a simple model. *Australian Forestry* **65**, 87–98. doi:10.1080/00049158.2002.10674859

Landsberg, J. (1985) Drought and dieback of rural eucalypts. *Australian Journal of Ecology* **10**, 87–90. doi:10.1111/j.1442-9993.1985.tb00868.x

Landsberg, J. (1988) Dieback of rural eucalypts: tree phenology and damage caused by leaf-feeding insects. *Australian Journal of Ecology* **13**, 251–267. doi:10.1111/j.1442-9993.1988.tb00973.x

Landsberg, J. (1990a) Dieback of rural eucalypts: does insect herbivory relate to dietary quality of tree foliage? *Australian Journal of Ecology* **15**, 73–87. doi:10.1111/j.1442-9993.1990.tb01022.x

Landsberg, J. (1990b) Dieback of rural eucalypts: response of foliar dietary quality and herbivory to defoliation. *Australian Journal of Ecology* **15**, 89–96. doi:10.1111/j.1442-9993.1990.tb01023.x

Landsberg, J. (1990c) Dieback of rural eucalypts: the effect of stress on the nutritional quality of foliage. *Australian Journal of Ecology* **15**, 97–107. doi:10.1111/j.1442-9993.1990.tb01024.x

Landsberg, J. and Cork, S. (1997) Herbivory: interactions between eucalypts and the vertebrates and invertebrates that feed on them. In: Williams, J.E. and Woinarski, J.C.Z. (eds) *Eucalypt Ecology: Individuals to Ecosytems*. Cambridge University Press, Cambridge, pp. 342–371.

Landsberg, J. and Wylie, F. (1983) Water stress, leaf nutrients and defoliation: a model of dieback of rural eucalypts. *Australian Journal of Ecology* **8**, 27–41. doi:10.1111/j.1442-9993.1983.tb01516.x

Landsberg, J. and Wylie, F. (1988) Dieback of rural trees in Australia. *GeoJournal* **17**, 231–237. doi:10.1007/BF02432927

Landsberg, J., Morse, J. and Khanna, P. (1990) Tree dieback and insect dynamics in remnants of native woodlands on farms. *Australian Ecosystems: 200 Years of Utilisation, Degradation and Reconstruction. Proceedings of the Ecological Society of Australia* **16**, 149–165.

Lunt, I. (1998) *Allocasuarina* (Casuarinaceae) invasion of an unburnt coastal woodland at Ocean Grove, Victoria: structural changes 1971–1996. *Australian Journal of Botany* **46**, 649–656. doi:10.1071/BT97032

Mackay, S., Humphreys, F., Clark, R., Nicholson, D. and Lind, P. (1984) *Native Tree Dieback and Mortality on the New England Tablelands of New South Wales*. Forestry Commission of NSW, Sydney.

Manion, P. (1981) *Tree Disease Concepts*. Prentice-Hall Inc., Englewood Cliffs, NJ, 399 pp.

Mapondera, T., Burgess, T., Matsuki, M. and Oberprieler, R. (2012) Identification and molecular phylogenetics of the cryptic species of the *Gonipterus scutellatus* complex (Coleoptera: curculionidae: Gonipterini). *Austral Entomology* **51**, 175–188. doi:10.1111/j.1440-6055.2011.00853.x

Matsuki, M. and Tovar, F. (2010) IPMG Pests Notes—Gonipterus. Western Australia: Industry Pest Management Group. 2 pp. Accessed 31 July 2015. Available from http://plantationhealth.com.au/pdf/pestnotes/gonipterus.pdf

McElhinny, C., Gibbons, P. and Brack, C. (2006) An objective and quantitative methodology for constructing an index of stand structural complexity. *Forest Ecology and Management* **235**, 54–71. doi:10.1016/j.foreco.2006.07.024

Murphy, B. and Timbal, B. (2008) A review of recent climate variability and climate change in southeastern Australia. *International Journal of Climatology* **28**, 859–879. doi:10.1002/(ISSN)1097-0088

Newete, S., Oberprieler, R. and Byrne, M. (2011) The host range of the eucalyptus weevil, *Gonipterus "scutellatus"* Gyllenhal (Coleoptera: curculionidae) in South Africa. *Annals of Forest Science* **68**, 1005–1013. doi:10.1007/s13595-011-0108-9

Ohmart, C. and Edwards, P. (1991) Insect herbivory on *Eucalyptus*. *Annual Review of Entomology* **36**, 637–657. doi:10.1146/annurev.en.36.010191.003225

Old, K. (2000) Eucalypt diseases of complex etiology. *In*: Keane, P.J., Kile, G.A., Podger, F.D. and Brown, B.N. (eds) *Diseases and Pathogens of Eucalypts*. CSIRO Publishing, Melbourne, pp. 411–425.

Phillips, C. (1992) Eucalyptus Weevil. Fact Sheet Number 7, revised November 2007. Primary Industries and Resources, Government of SA (PIRSA). 3 pp. Available from www.pir.sa.gov.au/__data/assets/pdf_file/0014/32900/Number_7_Eucalyptus_Weevil.pdf

Pook, E. and Forrester, R. (1984) Factors influencing dieback of drought-affected dry sclerophyll forest tree species. *Australian Forest Research* **14**, 201–217.

Price, P. (1991) The plant vigor hypothesis and herbivore attack. *Oikos* **62**, 244–251. doi:10.2307/3545270

Price, P.W., Cobb, N., Craig, T.P., Fernandes, G.W., Itami, J.K., Mopper, S. and Preszler, R.W. (1990) Insect herbivore population dynamics on trees and shrubs: new approaches relevant to latent and eruptive species and life table development. In: Bernays, E. (ed.) *Insect–Plant Interactions*. CRC Press, Boca Raton, FL, pp. 1–38.

Rice, K.J., Matzner, S.L., Byer, W. and Brown, J.R. (2004) Patterns of tree dieback in Queensland, Australia: the importance of drought stress and the role of resistance to cavitation. *Oecologia* **139**, 190–198. doi:10.1007/s00442-004-1503-9

Rivera, A., Carbone, S. and Andres, J. (1999) Life cycle and biological control of the Eucalyptus snout beetle (Coleoptera, Circulionidae) by Anaphes nitens (Hymenoptera, Myrmaridae) in north-west Spain. *Agricultural and Forest Entomology* **1**, 103–109.

Stange, E. and Ayres, M. (2010) Climate change impacts: insects. In: *Encyclopaedia of Life Sciences (ELS)*. John Wiley and Sons Ltd, Chichester.

Stone, C., Kathuria, A., Carney, C. and Hunter, J. (2008) Forest canopy health and stand structure associated with bell miners (*Manorina melanophrys*) on the central coast of New South Wales. *Australian Forestry* **71**, 294–302. doi:10.1080/00049158.2008.10675048

Taylor, G. and Roach, I. (2003) Monaro region, New South Wales. Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME), Canberra. 6 pp. Accessed 31 July 2015. Available from http://crcleme.org.au/RegLandEvol/Monaro.pdf

Tooke, F. (1953) The eucalyptus snout-beetle, *Gonipterus scutellatus* Gyll. A study of its ecology and control by biological means. *In*: *Entomology Memoirs*. Department of Agriculture, Union of South Africa, Govt Printer, Cape Town, pp. 1–282.

Turner, J., Lambert, M., Jurskis, V. and Bi, H. (2008) Long term accumulation of nitrogen in soils of dry mixed eucalypt forest in the absence of fire. *Forest Ecology and Management* **256**, 1133–1142. doi:10.1016/j.foreco.2008.06.021

White, T. (1969) An index to measure weather-induced stress of trees associated with outbreaks of psyllids in Australia. *Ecology* **50**, 905–909. doi:10.2307/1933707

White, T. (1986) Weather, *Eucalyptus* dieback in New England, and a general hypothesis of the cause of dieback. *Pacific Science* **40**, 58–78.