# Landscape processes and eucalypt dieback associated with bell miner habitat in south-eastern Australia

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## Summary

In this paper, we review current knowledge concerning the relationship between bell-miner-associated dieback and landscape-scale processes. We consider land clearing and fragmentation, logging and associated disturbances, fire and grazing regimes, weed establishment, nutrient changes, pathogenic factors and hydrological factors, while recognising that these factors interact. A case study from Toonunbar State Forest illustrates the complexity of factors involved in this form of dieback.

*Keywords*: forest management; landscape ecology; literature reviews; dieback; herbivores; psyllids; bell miner; *Manorina melanophrys*; *Eucalyptus*; Australia

## Introduction

During the early 1990s, canopy dieback was increasingly recognised in the remnant eucalypt forests of south-eastern Australia, coincident with regional increases in populations of bell miners (*Manorina melanophrys*). Bell-miner-associated dieback (BMAD) became noted for its rapid expansion and severe effect on the overstorey canopy, leading to concerns of fundamental changes in species composition and more general effects on the biota and landscape of the region (Billyard 2004). An account of the development of BMAD is given in Wardell-Johnson *et al*. (2005a, this issue; b). The causes of BMAD remain largely unresolved, though they appear to be multi-dimensional and related to complex interactions at a range of scales. Stone (2005, this issue) considers BMAD from the tree crown scale, while this paper examines the forest stand and landscape scales, and provides a review of landscape processes and dieback associated with bell miner habitat in south-eastern Australia.

## Interactions between disturbances, stress and bell-miner-associated dieback

Many forms of disturbance have provided forces of evolutionary significance in Australia (Gill 1981). However, the intensity and extent of some influences have been considerably exacerbated, and forms of disturbance without precedent in the Australian environment have been added since European settlement (Wardell-Johnson and Nichols 1991; Calver and Wardell-Johnson 2004; Lunney 2004). It is likely that the interactions between various agents of disturbance might have greater ecological effects than those of any particular agent (Burrows and Wardell-Johnson 2003). For example, convincing links have been hypothesised between plant disease, introduced species, fire and logging (Shearer and Tippett 1989; Wardell-Johnson and Nichols 1991; Young 1994; Garkaklis *et al.* 2004), and between nutrients, birds, fragmentation and rural dieback (Landsberg and Wylie 1991; Clarke and Schedvin 1999). Numerous authors (e.g. Landsberg and Wylie 1991; Wylie *et al.* 1993; Stone *et al.* 1995) have identified insect outbreaks as part of feedback loops associated with disturbance and consequent dieback or death of eucalypts in rural and forested landscapes.

It has been proposed that these interactions affect levels of herbivory and psyllid outbreaks in accordance with variations in environmental conditions within eucalypt-dominated ecosystems. The 'Plant Stress Hypothesis' proposes that new foliage of stressed plants contains elevated concentrations of plant nutrients (especially nitrogen and phosphorus) and volatiles, and that these high nutrient levels increase the survival and growth of herbivores (White 1969, 1984, 1993; Landsberg and Cork 1997; Wardle *et al.* 2004; Finlay-Doney and Walter 2005). In contrast, the 'Plant Vigour Hypothesis' suggests that enhanced nutritional quality of trees affected by dieback is associated with favourable growing conditions rather than environmental stress (Landsberg 1990a; Stone 2001).

Rather than being strict alternatives, these hypotheses represent two ends of a spectrum (Landsberg and Cork 1997). Both hypotheses may explain contrasting patterns of insect outbreaks (Price 1991, 1992). There has been insufficient research to determine the interactions between stress and vigour with respect to BMAD, and the situation is likely to be more complex than would be expected with one or the other as driver. Stone (2005, this issue) examines the issue at the scale of the tree crown and concludes that vigorously growing trees initially allow a population build-up of psyllids, with stress being induced by incapacity of the trees to maintain crown condition. The ability of a tree to replace foliage more quickly than it is lost through herbivory will be a factor in BMAD.

### Land clearing and fragmentation

Land clearing and forest fragmentation are recognised as major threats to biodiversity (Saunders *et al.* 1991; Laurance *et al.* 1998), and have had a relatively long history in north-eastern

NSW. Lowland rainforests, in particular, were targeted for conversion to agriculture from about 1860 to the early 20th century (Webb 1956; Kanowski *et al.* 2003). In addition to more than 99% of the 75 000 ha Big Scrub subtropical rainforest, dense forests of *Eucalyptus*, *Melaleuca*, *Allocasuarina* and rainforests were extensively cleared, and open grassy woodlands were converted to agricultural land (Lott and Duggin 1993; Jurskis 2000).

Apart from the loss of habitat, fragmentation (including internal fragmentation, Goosem 1997) causes associated edge effects. Elevated wind speed and turbulence, and increased light penetration at edges, result in greater air and soil temperature fluctuations compared to forest interiors (Turton and Freiburger 1997). Consequently, local evaporation increases while relative humidity and soil moisture decrease (Murcia 1995). Higher light levels promote the growth of plants such as weeds, pioneer species and woody vines (Laurance 1991; Wardell-Johnson *et al.* 2005c). Changes in species composition due to these habitat alterations may also have consequences for ecological processes such as pollination, dispersal, competition or predation (Murcia 1995; Kanowski *et al.* 2005).

The profound impacts of fragmentation have been demonstrated locally. For example, interactions between fragmentation and aggressive colonial birds have led to changes in bird composition and diversity (Catterall *et al.* 2002; Piper and Catterall 2003; Catterall 2004; Chan 2004). In particular, increases in populations of noisy miners (a species closely related to bell miners but with different habitat requirements) have been strongly linked to edge effects (Catterall *et al.* 2002; Piper and Catterall 2003; Catterall 2004). It should be noted that large forest blocks may act as fragments once changes initiated at edges become more widespread in a forest block (Laurance 1990).

However, there have not been any studies on fragmentation directly associated with BMAD. Michael Clarke (Department of Zoology, La Trobe University, 2005 *pers. comm.*) associates BMAD with habitat fragmentation because he has noted that most bell miner colonies continually shift, albeit over only short distances (Clarke and Fitz-Gerald 1994). Bell miner colonies are more spatially restricted in small remnants, leading to localised concentrations of impacts. However, some forests in the Watagans and Richmond/Border Ranges of north-eastern NSW have dieback patches that have spread between gullies. In these areas, spatially continuous bell miner colonies occur in apparently continuous forest.

### Logging and associated disturbances

Logging can have profound effects on forest biota (Calver and Wardell-Johnson 2004; Lindenmayer and Gibbons 2004; Wardell-Johnson and Calver 2005) through marked alterations of forest age and population structure, species composition, understorey density, canopy cover and hydrology. In farming areas, agricultural clearing and introduced species have more significant impacts on biodiversity than logging and its associated activities (Wardell-Johnson and Nichols 1991; Braithwaite 2004; Calver and Wardell-Johnson 2004). Nevertheless, logging disturbances are widespread and continuing in Australian forests. Logging rainforest in northern NSW stopped in the 1980s and most local areas of rainforest are now in conservation reserves. However, there has been a concurrent increase in logging of eucalypt forests in the same region (Pugh and Flint 1999). Current quota commitments require relatively rapid return times in many north-east forests, leaving them dominated by trees less than 50 y old (Flint *et al.* 2004).

Logging leaves a legacy of a younger, more open forest canopy and an environment strikingly different to that noted by the first European visitors (Calver and Wardell-Johnson 2004). More importantly, the changes associated with a broad-scale native forest timber industry have interacted with other threatening processes, such as changed fire regimes, introduced species (Rhind 2004; Wardell-Johnson *et al.* 2004) and plant disease (Calver and Wardell-Johnson 2004; Garkaklis *et al.* 2004). Logging alters the overstorey and understorey plant composition, and, especially with altered fire regimes, also alters the composition and abundance of fauna (Gentle and Duggin 1997; Lunney 2004; Wardell-Johnson *et al.* 2004), including in northern NSW (Lunney and Matthews 2004; Kanowski *et al.* 2005). The duration of these changes is dependent on forest type, post-logging management practices (e.g. fire management, thinning of regrowth), the frequency and intensity of logging, and climate (Kavanagh and Stanton 2003).

Many, if not all, of these impacts are relevant to BMAD as they have the potential to expand psyllid populations and facilitate bell miner colonisation. The conversion of large areas of mature stable environments to highly stocked or disturbed regrowth stands represents a major structural change to the forests (Bower 1998; Calver and Wardell-Johnson 2004). The structural changes include associated changes in species composition (flora and fauna, including exotic species), plant productivity and nutrient content, and also hydrological processes in the short to medium term (Cornish 1993; Cornish and Vertessy 2001; Vertessy *et al.* 2001). Bower (1998) noted that sites with large bell miner colonies appeared to have been highly disturbed by logging activities, and were often dominated by an almost impenetrable lantana (*Lantana camara*) shrub layer.

The simplified forest structure causes changes to light intensity and leaf phenology, hydrological and pathological processes, and may increase rates of soil nutrient mineralisation and uptake by trees. Tree removal increases light intensity in the overstorey, and may lead to vigorous shoot production, including epicormic shoots, on remaining trees (Stone 2005, this issue). Changes in light intensity and leaf phenology may also lead to insect outbreaks (Stone 2005, this issue; Stone in press).

Disturbance from logging increases the availability of resources necessary for plant growth, thus promoting rapid growth of the understorey (Turner and Lambert 1986; Kutt 1996). Additionally, increased levels of foliar nitrogen have the potential to allow expansion of a psyllid outbreak (Stone 2005, this issue). Vegetation dominated by regrowth or dieback-affected trees has a higher nutrient content than the same vegetation type dominated by older trees because the crowns are growing more vigorously (Landsberg and Wylie 1983; Landsberg 1990b). Foliar nitrogen content has been suggested as an important factor in psyllid outbreaks in eucalypt forests (Stone 2005, this issue). Therefore any activity or process that increases foliar nitrogen has the potential to allow expansion of a psyllid outbreak.

There have been many publications on the impacts of logging on the biota of eucalypt forests in Australia (reviews in Lunney 2004). However, few of these have addressed the BMAD problem. A notable exception is a study by Kavanagh and Stanton (2003) who measured bird abundance and species turnover during the medium term (13 and 22 y) after intensive logging. They found that a large component of the avifauna population had recovered within 22 y, and that bell miners had by then become abundant in moist gully forest. Kavanagh and Stanton (2003) associated disturbance from logging with the creation of bell miner habitat, even though there had been no immediate increase in bell miners (within four years of logging) as a dense understorey recovered, and even though other insectivorous birds of dense understorey vegetation had increased. Hence, their study may support the hypotheses that a dense and structurally diverse understorey excludes bell miner colonies unless there are also suitable food resources for them in the canopy. If this is so then suitable conditions in the canopy may be a primary factor in the initiation of bell miner colonies.

Nevertheless, Stone (1999) suggested that selective logging without effective overstorey regeneration encouraged dense understorey development, and that these conditions favour colonisation by bell miners. Hence, Stone (1999) suggested that changes to the overstorey may be sufficient to commence a spiral of dieback on some eucalypt forest sites.

Logging operations may be both implicated in the development of BMAD and affected by changes in yield induced by BMAD. Nevertheless, the literature is very limited concerning the impacts of logging and associated disturbances on the initiation or development of BMAD. The increased area of BMAD may significantly reduce timber yields from these eucalypt stands. These changes are likely in the medium-term as growth rates slow, weed species dominate, and species composition changes.

**Fire and grazing regimes**

Fire is the most readily available, broad-scale management tool in Australian ecosystems (Gill 1981), and the literature has attracted a greater share of advocacy papers than most other forest management issues. There has been considerable debate concerning the role of fire in Australian ecosystems (reviewed by Whelan 1995; Bradstock *et al.* 2002; Abbott and Burrows 2003). For the environments in which BMAD occurs, arguments have been presented promoting both more frequent (Jurskis 2000, 2002, 2004a,b) and less frequent fire (Benson and Redpath 2000; Henderson and Keith 2002).

Jurskis (2004a,b) has argued that the 'reinstatement' of more frequent fire regimes would better protect the general health of eucalypt ecosystems, and that this would be a conservative management regime in terms of the pre-European environment (Jurskis 2000). Jurskis (2004b) stated that recent reductions in fire frequency in forests have coincided with structural and floristic changes, as well as with an apparent decline in the 'health' of many eucalypt forests as understoreys have become denser and BMAD has expanded. Jurskis (2004b) also linked soil environments, microclimates, forest structure, flora and fauna to forest health, but argued that research should focus on manageable factors, such as fire and grazing systems, rather than on pests that are symptomatic of forest decline (Jurskis 2004a).

Alternatively, other authors (Benson and Redpath 2000; Henderson and Keith 2002; Keith and Henderson 2002; Wardell-Johnson *et al.* 2004) have argued that the position concerning fire history is complex, and that pre-European and pre-Aboriginal fire regimes would have differed between vegetation types, location and region. Benson and Redpath (1997) emphasised that at the time of European settlement, there was a wide variety of vegetation types, and a variety of frequencies of fire regimes. They challenged what they regarded as simplistic notions and unsubstantiated observations about the composition, structure and fire regimes in pre-European vegetation across south-eastern Australia as depicted in Flannery (1994) and Ryan *et al.* (1995).

While a mosaic-burning pattern would have applied to some types of vegetation, including grasslands and grassy woodlands, other vegetation, including shrubby forests and woodlands, were unlikely to have been frequently burnt (Benson and Redpath 1997). Henderson and Keith (2002) demonstrated that historical grazing and burning practices substantially simplified the woody understoreys of the forests of the north-eastern escarpment of NSW; species richness and population densities of woody species were lower where disturbance was more intensive.

All authors, regardless of their position on the historical frequency of fire in particular vegetation types (or more generally across the landscape), acknowledge the importance of fire in the shaping of the Australian biota, and in continuing ecosystem management. Most authors have, however, argued that there is a requirement for a better understanding of pre-European fire regimes and more clearly focused objectives. Management objectives would thus determine the types of fire regimes to be implemented. If the protection of biodiversity is a primary consideration, scientific evidence on the habitat requirements of biota should underpin proposed fire regimes (Benson and Redpath 2000). Defining the desired structure and floristic composition of forested environments is a larger issue than the debate about BMAD. Long-term, site-based survey or experimental evidence is essential in order to effectively resolve or advance the debate.

**Weed establishment and management**

The importance of invasive exotic organisms as major agents of land transformation, disrupters of ecosystem functioning, and threats to biodiversity has increased rapidly over the last 200 y, but particularly during the 20th century (Richardson *et al.* 1997). A small proportion of introduced plants (termed environmental weeds; Holzner and Humata 1982) can invade natural or semi-natural habitats.

Several such species have been implicated in the BMAD problem in north-eastern NSW. Because of the long period since initial clearing, and the high fertility and rainfall of the region, areas of north-eastern NSW subject to disturbance have been a haven for exotic plants. The shrub lantana (*L. camara*), in particular, has become a major weed of open eucalypt forest (Bower 1998; Wardell-Johnson *et al.* 2005c).

Many recent changes in agriculture and forest management have also increased the spread of lantana and a wide range of other weeds (Kanowski *et al.* 2003; Wardell-Johnson *et al.* 2005c). Disturbance and the opening of forest stands has been shown to increase dominance of lantana (or any other aggressive plant coloniser of disturbed patches), particularly where it is already widespread and common (Wardell-Johnson *et al.* 2005). Gentle and Duggin (1997) suggested that strategies to reduce weed encroachment and vegetation degradation must identify and maintain ecological barriers to prevent lantana invasion. However, lantana is already dominant in many locations impacted by BMAD. Thus, other management strategies need to be implemented in areas dominated by lantana.

Increases in light intensity and soil temperature stimulate the germination of lantana seeds and encourage vegetative propagation (Sharma *et al.* 1988). In the relatively high light levels beneath a eucalypt canopy, lantana can dominate the understorey and suppress regeneration of native plants. Gentle and Duggin (1997) found that canopy disturbances create patches of increased light availability and lead to invasion by lantana, indicating that shading may be a limiting factor. Therefore, while lantana may not be a primary cause of dieback in Sydney blue gum (*Eucalyptus saligna*), Stone (in press) found that its presence may contribute to the persistence of dieback. The presence of lantana may reflect decreased crown density; which facilitates vigorous foliage growth and the potential to support psyllid (and perhaps other insect) outbreaks. Newly-founded bell miner colonies may benefit from the presence of both high food supplies and suitable understorey structure for nesting.

Bower (1998) related the proliferation of lantana in his study areas largely to disturbance from logging activities and the improvement of conditions for lantana germination and recruitment. In eucalypt forest, lantana thickets increase the levels of soil organic carbon and nitrates which alters the natural nutrient cycle (Lamb 1980). Thus, broadscale habitat modification from intensive logging operations and subsequent lantana domination may favour the establishment of psyllids and bell miner colonies (Bower 1998).

Lantana cover tended to be higher in bell miner sites, but lantana also dominated some sites without bell miners (Bower 1998). Stone *et al.* (1995) found an association between lantana and bell miners, but concluded that it was not a linear trend and that bell miners appeared to use a dense midstorey for nesting sites irrespective of plant species composition. Bower (1998) found a correlation between poor understorey foliage cover and bell miner density. However, he remained unconvinced by this finding, given other research that bell miners favour dense, shrubby understoreys that are often dominated by weeds. Lantana may provide a dense but not complex habitat, thus disadvantaging birds preferring a complex understorey structure. In contrast, Gentle and Duggin (1997) did not clearly link colonies of bell miners with the occurrence of lantana.

High-intensity burns can be effective in controlling lantana, but Bower (1998) cautioned that most post-logging burns are of low or medium intensity and therefore ineffective at preventing resprouting of lantana. Additionally, Gentle and Duggin (1997) suggested that low to moderate-intensity control burns that are used to prevent more destructive fires appear to increase lantana invasion. They recommended fire suppression to reduce invasions, and the removal of cattle and feral herbivores, since the biomass reduction and soil disturbance associated with fire and cattle grazing increase the opportunity for lantana invasion.

Interactions between grazing, fire and weeds have major implications for biodiversity, not just for the incidence of bell miners. The number and diversity of insectivorous birds is reduced in remnant stands affected by rural dieback because of the loss of shrub cover through disturbance by livestock (Ford and Bell 1981; Ford 1985; Loyn 1985; Landsberg *et al.* 1990). In relatively undisturbed eucalypt forest where there are bell miner colonies but not dieback, the understorey tends to be relatively structurally diverse. A structurally diverse understorey that favours a diverse avifauna may be antagonistic to bell miner colonisation. However, it is also likely that conversion of a structurally diverse understorey to a grassy understorey with few shrubs will disadvantage bell miners. In these circumstances, high numbers of weeds can exacerbate the consequences for biodiversity.

Bower (1998) stated that the inability of lantana-dominated areas to regenerate affects the succession of a structurally complex forest ecosystem. He suggested that lantana control may disrupt bell miner colonies and stimulate a more structurally complex native flora; and weed removal would initiate, release and facilitate natural regenerative processes and promote establishment of structurally complex mid and lower strata. However, prevention of lantana reinvasion requires the establishment of a dense, shade-producing canopy and regular, systematic follow-up maintenance (Kooyman 1996).

Hence the management of lantana requires a more integrated solution than reliance on changes in fire regimes. The best means of lantana control depends on site conditions and vegetation type, as well as the resources available for management programs and follow-up operations. Furthermore, the short- and long-term effects on local vegetation and biodiversity of various management regimes need further assessment before they can be predictable.

## Nutrients and other soil factors

There is a vast literature on nutrients and plant growth and on the forms of nitrogen (N) in soils and vegetation. For example, there have been many studies that demonstrated changes to N mineralisation associated with forest management activities (e.g. Adams and Attiwell 1982). Studies have also demonstrated that some herbivorous insect species respond to changes in foliar nutrition as a consequence of silvicultural practices (Waring *et al*. 1992). However, with the exception of a pilot study by Stone (in review), we are not aware of any studies that have attempted to resolve the interactions between forest management, soil nitrogen content, foliar nutrition, insect populations and bell miners, either through field-based research or experimentally. The existing literature is at best equivocal and will continue to attract controversy. Of particular importance is the relative weight that should be given to nutrient-related issues, floristics and structure in the BMAD problem. We suggest that research associated with forest structure will be more enlightening for the management of BMAD than research on more subtle processes. Forest structure influences many relevant, interrelated forest processes (including nutrients and other chemical constituents).

Jurskis and Turner (2002) have suggested that exclusion of low-intensity fire from eucalypt forests that evolved with fire leads to their progressive decline, and that any massive disturbance by wildfire is unlikely to regenerate these forests because insufficient seed will be available, and the weakened trees will be less able to resprout. They argue that intensive disturbance, such as clearing and plantation establishment, would be required to re-establish eucalypt ecosystems on sites where 'mesic' dieback is well advanced. They do not provide any data to allow validation or testing of the model presented, but suggest that validation of changed processes in forest soils and litter, as well as physiological changes in trees on dieback sites compared to healthy sites would confirm the model. They also propose that monitoring of tree health after cutting and burning understorey vegetation in mesic dieback areas on the NSW coast could be used to test the model.

Stone (in press) has attempted to test the model presented by Jurskis and Turner (2002) by linking dieback, leaf and soil properties. She used a survey approach to compare leaf, tree and soil properties associated with moist sclerophyll forest exhibiting canopy dieback in Cumberland State Forest at West Pennant Hills, NSW. She made detailed measurements on six 20-m-radius plots and found that the plot permanently colonised by bell miners also had Sydney blue gum in the poorest condition. While no consistent relationship could be found between the stand condition and either lantana or the soil pathogen *Phytophthora cinnamomi*, there were significant correlations between foliar traits associated with insect damage, free amino acid content and relative chlorophyll content. While this study had a limited number of sample sites, making results equivocal, Stone (pers. comm.) has demonstrated that models, such as that presented by Jurskis and Turner (2002), can be critically tested.

**Pathogenic factors**

Soil pathogens have considerable influence on the health of affected forest stands. Many pathogens have become widespread through the transport of soil in road building, mining, logging operations and fire control, and continue to spread and intensify (Garkaklis *et al.* 2004). Bushwalking and other activities responsible for more limited soil movement have also been implicated in the spread of pathogens (Garkaklis *et al.* 2004). The impacts of the introduced plant pathogen *Phytophthora cinnamomi* on Australian forest flora are considered significant on a global scale (Shearer *et al*. 2004). A recent review (Garkaklis *et al.* 2004) argued that some impacts on forest fauna have been noted, and the potential threats to fauna through structural and floristic changes are likely to be pronounced. *Phytophthora cinnamomi* is now widespread in a variety of vegetation communities in humid areas of all Australian states (but not the Northern Territory).

Various pathogens, such as species of *Phytophthora*, *Armillaria*, *Pythium* and *Fusarium*, have been sampled from stands of Sydney blue gum affected by psyllid-associated dieback in NSW, as well as from areas of healthy forest (Stone *et al.* 1995). In addition, wood-boring insects (e.g. termites; hepialid and cossid moths; longicorn beetle larvae) are also commonly found in the stems of eucalypts with crown dieback (Stone *et al.* 1995), suggesting that once canopy dieback has commenced many other interacting factors facilitate canopy decline. The various factors in the development of canopy dieback have not, however, been separated. Nevertheless, the incidence and impacts of *Phytophthora* are now more widely recognised as a serious problem of south-western Australia, Tasmania and south-eastern Australia. Any activity which increases soil movement or soil disturbance has the potential to increase the impact of soil-water-borne pathogens on a forest stand.

Clarke and Schedvin (1999) noted that conclusions concerning the impacts of bell miners in their study in Victoria were compromised by the presence of *Phytophthora* in their study sites. *Phytophthora cinnamomi* was also detected in five of Stone's (in press) six bell miner sites, but the presence of this soil pathogen was not well correlated with crown condition of Sydney blue gum. Despite the hypothesised association of disease and other agents of disturbance associated with BMAD, there has been no rigorous analysis. This is despite convincing links between plant disease, introduced species, fire and logging elsewhere (Shearer and Tippett 1989; Wardell-Johnson and Nichols 1991; Young 1994; Garkaklis *et al.* 2004).

**Hydrological factors**

There is evidence that total evapotranspiration in regrowth forests exceeds that in old growth forests or forests dominated by relatively old trees, and concern has been expressed concerning the implications of high densities of regeneration in eucalypt forests (Florence 1996). High stocking rates can result in reductions in water yields from regrowth forests (Cornish 1993; Cornish and Vertessy 2001; Vertessy *et al.* 2001). It has been increasingly recognised that pathogen-related problems are closely linked with hydrology. For example, many forms of disturbance, including road-building, mining and logging, can affect the hydrology of a site. Davison (1997) suggested that death of jarrah (*E. marginata*) trees in south-western Australia originally attributed to pathogenic invasion may actually have been due to waterlogging, the converse of the problem associated with dense forest stands. Davison (1997) stated that such deaths are likely to become more frequent with decline in the mean basal area of forest stands.

## Toonunbar — a case study of interactions in bell-miner-associated dieback

Toonunbar State Forest is an area with particularly severe BMAD. The history of this area is well known locally. Bob O'Neil (2005 *pers. comm.*) has lived all his life in the immediate area. He recalls that, prior to about 1968, the vegetation of this sandstone plateau consisted of Sydney blue gum grassy woodland bounded on three sides by rainforest and the fourth by a sandstone cliff. The sandstone area (frequently outcropping) is overlain by a veneer of basalt-derived soil, which increases in depth as the terrain falls away from the plateau, the sandstone outcropping becomes no longer visible, and the woodland changes to rainforest. The old sharp boundaries to the rainforest remain visible, although young rainforest has blurred them.

Toonunbar State Forest was grazed by cattle until 1956 when the cattle were removed due to an inability to control cattle ticks. The area had been lightly logged in the early 20th century for railway sleepers. However, the first major logging operation in the area occurred in the early to late 1960s, with most logging prior to 1968. In 1968, a high intensity fire burnt the area and a dense stand of Sydney blue gum resulted from seed germination on the high-nutrient soil veneer. This subsequent dense pole stand was considered highly productive during the early 1990s, although the understorey was, by then, dense lantana.

It is likely that a dense stand of Sydney blue gum could not be supported indefinitely by the sandstone substrate. Thus a build-up of psyllids may have initially been facilitated by the vigorous canopies of the pole stand of Sydney blue gum, but that the stand was unable to maintain a healthy crown in the face of high populations of psyllids, as well as water or nutrient limitations. For bell miners, the overstorey may have provided an abundant food resource while the dense stand of lantana that resulted from the disturbance associated with logging and fire provided suitable nesting habitat. Virtually the whole of this plateau area is now severely affected by canopy dieback. In this case, hydrology, disturbance and bell miners appear to have interacted, leading to a spiral of eucalypt canopy decline. The build up in the population of psyllids and hence bell miners now appears to have moved beyond the plateau to more marginal eucalypt forest on the steeper slopes.

This case study illustrates that no one factor is likely to be isolated as the cause of BMAD. It also illustrates the need for accurate information on the management history of an area so that biotic influences can be seen within an appropriate management context. A more detailed investigation involving plots and management history as well as appropriate multivariate analysis approaches may be necessary to provide a required context for BMAD, and to suggest appropriate research directions at the landscape scale.

## Conclusion

There is a vast literature relevant to landscape processes, disturbance and BMAD, although relatively little directly illuminating the various debates that surround it. Evidence from linking several fields suggests that management practices which create habitats with a structure and floristic composition favouring the establishment of bell miner colonies are more likely to favour the establishment of psyllid outbreaks, and vice versa. In such situations, colonisation by bell miners will lead to the exclusion of other avian insectivores, resulting in an increase in the numbers of psyllids. However, the generally poor understanding of the geographic distribution of BMAD prevents the disentangling of alternative hypotheses.

There is a need to investigate the structure and floristics of the habitat favoured by bell miners, regardless of whether they are the direct or indirect causes of a eucalypt forest-dieback problem. It may be appropriate for management to reduce the creation of habitat preferred by bell miners, as such habitat may also facilitate the primary cause of eucalypt dieback. However, to attempt such management intervention in isolation from an understanding of both the processes and the behaviour of bell miners under different levels and types of disturbance may compound the problem. An understanding of this problem will be necessary to achieve resolution. At stake is the conservation of an internationally significant region of north-eastern NSW as well as the sustainability of the regional timber industry.

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## References

Abbott, I. and Burrows, N. (eds) (2003) *Fire in Ecosystems of South-West Western Australia: Impacts and Management.* Backhuys Publishers, Leiden, The Netherlands.

Adams, M.A. and Attiwill, P.M. (1982) Nitrogen mineralization and nitrate reduction in forests. *Soil Biology and Biochemistry* **14,** 197–202.

Benson, J.S. and Redpath, P.A. (1997) The nature of pre-European native vegetation in Australia: a critique of Ryan, D.G., Ryan, J.R. and Starr, B.J. (1995) *Australian Landscape: Observations of Explorers and Early Settlers. Cunninghamia* **5,** 285–328.

Benson, J.S. and Redpath, P.A. (2000) 1. Vegetation and fire. Responses to V. Jurskis in Volume 63(3). *Australian Forestry* **64,** 64–65.

Billyard, R. (2004) BMAD Working Group perspective on forest decline and potential management solutions. In: White, T.C.R. and Jurskis, V. (eds) *Fundamental Causes of Eucalypt Forest Decline and Possible Management Solutions, Proceedings of Colloquium.* State Forests of NSW, Sydney, pp. 31–32.

Bower, H. (1998) For whom the bell tolls: interactions between bell miners, eucalypt dieback and bird communities in north-east NSW. Honours thesis, Southern Cross University, Lismore, NSW.

Bradstock, R.A., Williams, J.E. and Gill, A.M. (eds) (2002) *Flammable Australia.* Cambridge University Press, Cambridge.

Braithwaite, W. (2004) Do current forestry practices threaten forest fauna? A perspective. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 513–536.

Burrows, N. and Wardell-Johnson, G.W. (2003) Fire and plant interactions in forested ecosystems of south-west Australia; a review. In: Abbott, I. and Burrows, N. (eds) *Fire in Ecosystems of South-West Western Australia: Impacts and Management.* Backhuys Publishers, Leiden, The Netherlands, pp. 225–268.

Calver, M. and Wardell-Johnson, G. (2004) Sustained unsustainability? An evaluation of evidence for a history of overcutting in the jarrah forests of Western Australia and its consequences for fauna conservation. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 94–114.

Catterall, C.P. (2004) Birds, garden plants and suburban bushlots: where good intentions meet unexpected outcomes. In: Lunney, D. and Bergin, S. (eds) *Urban Wildlife: More than Meets the Eye*. Royal Zoological Society of New South Wales, Mosman, pp. 21–31.

Catterall, C.P., Piper, S.D. and Goodall, K. (2002) Noisy miner irruptions associated with land use by humans in south-east Queensland: causes, effects and management implications. In: Franks, A., Playford, J. and Shapcott, A. (eds) *Landscape Health in Queensland*. Royal Society of Queensland, Brisbane, pp. 117–127.

Chan, K. (2004) Effect of patch size and bird aggression on bird species richness: a community-based project in tropical/subtropical eucalypt woodland. *Proceedings of the Royal Society of Queensland* **111,** 1–11.

Clarke, M.F. and Fitz-Gerald, G.F. (1994) Spatial organization of the cooperatively breeding bell miner *Manorina melanophrys*. *Emu* **94,** 96–105.

Clarke, M.F. and Schedvin, N. (1999) Removal of bell miners *Manorina melanophrys* from *Eucalyptus radiata* forest and its effect on avian diversity, psyllids and tree health. *Biological Conservation* **88,** 111–120.

Cornish, P.M. (1993) The effects of logging and forest regeneration on water yields in a moist eucalypt forest in NSW. *Journal of Hydrology* **150,** 301–322.

Cornish, P.M. and Vertessy, R.A. (2001) Forest age-induced changes in evapotranspiration and water yield in a eucalypt forest. *Journal of Hydrology* **242,** 43–63.

Davison, E.M. (1997) Are jarrah (*Eucalyptus marginata*) trees killed by *Phytophthora cinnamomi* or waterlogging? *Australian Forestry* **60,** 116–124.

Finlay-Doney, M. and Walter, G.H. (2005) Discrimination among host plants (*Leucaena* species and accessions) by the psyllid pest *Heteropsylla cubana* and implications for understanding resistance. *Agricultural and Forest Entomology* **7,** 153–160.

Flannery, T. (1994) *The Future Eaters.* Reed Books, Melbourne.

Flint, C., Pugh, D. and Beaver, D. (2004) The good, the bad and the ugly: science, process and politics in forestry reform and the implications for conservation of forest fauna in north-east New South Wales. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 222–255.

Florence, R.G. (1996) *Ecology and Silviculture of Eucalypt Forests*. CSIRO Publishing, Australia, 413 pp.

Ford, H.A. (1985) The bird community in eucalypt woodland and eucalypt dieback in the northern tablelands of New South Wales. In: Keast, A., Recher, H.F., Ford, H.A. and Saunders, D. (eds) *Birds of Eucalypt Forests and Woodlands: Ecology, Conservation and Management*. Surrey Beatty and Sons and the Royal Australasian Ornithologists Union, Sydney, pp. 333–340.

Ford, H.A. and Bell, H. (1981) Density of birds in eucalypt woodland affected to varying degrees by dieback. *Emu* **81,** 202–208.

Garkaklis, M.J., Calver, M.C., Wilson, B.A. and Hardy, G.E.St.J. (2004) Habitat alteration caused by introduced plant disease: a significant threat to the conservation of Australian forest fauna. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 899–913.

Gentle, C.B. and Duggin, J.A. (1997) *Lantana camara* L. invasions in dry rainforest–open forest ecotones: the role of disturbances associated with fire and cattle grazing. *Australian Journal of Ecology* **22,** 298–306.

Gill, A.M. (1981) Adaptive responses of Australian vascular plant species to fire. In: Gill, A.M., Groves, R.H. and Noble, I. (eds) *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 243–272.

Goosem, M. (1997) Internal fragmentation: the effects of roads, highways and powerline clearings on movements and mortality of rainforest vertebrates. In: Laurance, W.F. and Bierregaard Jr, R.O. (eds) *Tropical Forest Remnants: Ecology, Management and Conservation of Fragmented Communities*. University of Chicago Press, Chicago, pp. 241–255.

Henderson, M.K. and Keith, D.A. (2002) Correlation of burning and grazing indicators with composition of woody understorey flora of dells in a temperate eucalypt forest. *Austral Ecology* **27,** 121–131.

Holzner, W. and Humata, N. (eds) (1982) *Biology and Control of Weeds*. Junk, The Hague.

Jurskis, V. (2000). Vegetation changes since European settlement of Australia: an attempt to clear up some burning issues. *Australian Forestry* **63,** 166–173.

Jurskis, V. (2002) Restoring the prepastoral condition. *Austral Ecology* **27,** 689–690.

Jurskis, V. (2004a) Observations of eucalypt decline in temperate Australian forests and woodlands. 2004 Gottstein Fellowship Report. Gottstein Trust, Melbourne.

Jurskis, V. (2004b) The role of changed fire regimes in the apparent decline of eucalypts in temperate Australia. In: 11th Annual AFAC Conference and Inaugural Bushfire CRC Conference, 7–9 October 2004. Perth, Western Australia.

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

Kanowski, J., Catterall, C.P., Wardell-Johnson, G.W., Proctor, H. and Reis, T. (2003) Development of forest structure on cleared rainforest land in eastern Australia under different styles of reforestation. *Forest Ecology and Management* **183,** 265–280.

Kanowski, J., Catterall, C.P. and Wardell-Johnson, G.W. (2005) Consequences of broadscale timber plantations for biodiversity in cleared rainforest landscapes of tropical and subtropical Australia. *Forest Ecology and Management* **208,** 359–372.

Kavanagh, R.P. and Stanton M.A. (2003) Bird population recovery 22 years after intensive logging near Eden, New South Wales. *Emu* **103,** 221–231.

Keith, D.A. and Henderson, M.K. (2002) Restoring the prepastoral condition: response to Jurskis. *Austral Ecology* **27,** 691–693.

Kooyman, R.M. (1996) *Growing Rainforest: Rainforest Restoration and Regeneration.* Recommendations for the humid sub-tropical region of northern NSW and southeast Queensland. Greening Australia and State Forests of NSW.

Kutt, A.S. (1996) Bird population density in thinned, unthinned and old lowland regrowth forest, East Gippsland, Victoria. *Emu* **96,** 280–284.

Lamb, D. (1980) Soil nitrogen mineralisation in a secondary rainforest succession. *Oecologia* **47,** 257–263.

Landsberg, J. (1990a) Dieback of rural eucalypts: the effect of stress on the nutritional quality of foliage. *Australian Journal of Ecology* **15,** 97–107.

Landsberg, J. (1990b) Dieback of rural eucalypts: does insect herbivory relate to dietary quality of tree foliage? *Australian Journal of Ecology* **15,** 73–87.

Landsberg, J. and Cork, S.J. (1997) Herbivory: interactions between eucalypts and the vertebrates and invertebrates that feed on them. In: Williams, J. and Woinarski, J. (eds) *Eucalypt Ecology: Individuals to Ecosystems*. Cambridge University Press, Cambridge, pp. 342–372.

Landsberg, J. and Wylie, F.R. (1983) Water stress, leaf nutrients and defoliation: a model of dieback of rural eucalypts. *Australian Journal of Ecology* **8,** 27–41.

Landsberg, J. and Wylie, F.R. (1991) A review of rural dieback in Australia. In *Growback '91*. Growback Publications and Greening Australia, Melbourne, pp. 3–11.

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

Laurance, W.F. (1990) Comparative responses of five arboreal marsupials to tropical forest fragmentation. *Journal of Mammalogy* **71,** 641–653.

Laurance, W.F. (1991) Edge effects in tropical forest fragments: application of a model for the design of nature reserves. *Biological Conservation* **57,** 205–219.

Laurance, W.F., Ferreira, L.V., Rankine-de Merona, J.M. and Laurance, S.G. (1998) Rain forest fragmentation and the dynamics of Amazonian tree communities. *Ecology* **79,** 2032–2044.

Lindenmayer, D. and Gibbons, P. (2004) On charcoal, the increased intensity of logging and a flawed environmental impact process. In: Lunney, D. (ed.) *Conservation of Australia's Forest Faun*a, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 56–62.

Lott, R.H. and Duggin, J.A. (1993) *Conservation Significance and Long-term Viability of Sub-tropical Remnants of the Big Scrub, North-eastern New South Wales*. Report to Australian Heritage Commission and Department of Planning (NEP 90/36). Department of Ecosystem Management, University of New England, Armidale.

Loyn, R.H. (1985) Bird populations in successional forests of mountain ash *Eucalyptus regnans* in central Victoria. *Emu* **85,** 213–230.

Lunney, D. (ed.) (2004) *Conservation of Australia's Forest Fauna*, 2nd edn. The Royal Zoological Society of New South Wales, Mosman, NSW.

Lunney, D. and Matthews, A. (2004) Conserving the forest mammals of New South Wales. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, NSW, pp. 988–1021.

Murcia, C. (1995) Edge effects in fragmented forests: implications for conservation. *Trends in Ecology and Evolution* **10,** 58–62.

Piper, S.D. and Catterall, C.P. (2003) A particular case and a general pattern: hyperaggressive behaviour by one species may mediate avifaunal decreases in fragmented Australian forests. *Oikos* **101,** 602–614.

Price, P.W. (1991) The plant vigour hypothesis and herbivore attack. *Oikos* **62,** 244–251.

Price, P.W. (1992) Plant resources as the mechanistic basis for insect herbivore population dynamics. In: Hunter, M.D., Ohgushi, T. and Price, P.W. (eds) *Effects of Resource Distribution on Animal–Plant Interactions*. Academic Press, San Diego, pp. 139–173.

Pugh, D. and Flint, C. (1999) The magic pudding, the "cut-an'-come-again" forests. A preliminary appraisal of State Forests' Forest Resource and Management System (FRAMES). Unpublished report for the North East Forest Alliance.

Rhind, S.G. (2004) Direct impacts of logging and forest management on the brush-tailed phascogale *Phascogale tapoatafa* and other arboreal marsupials in a jarrah forest of Western Australia. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 639–655.

Richardson, D.M., Macdonald, L.A.W., Hoffmann, J.H. and Henderson, L. (1997) Alien plant invasions. In: Cowling, R.M., Richardson, D.M. and Pierce, S.M. (eds) *Vegetation of Southern Africa*. Cambridge University Press, Cambridge, pp. 535–570.

Ryan, D.G., Ryan, J.E. and Starr, B.J. (1995) *The Australian Landscape — Observations of Explorers and Early Settlers.* Murrumbidgee Catchment Management Committee, Wagga Wagga, NSW.

Saunders, D.A., Hobbs, R.J. and Margules, C.R. (1991) Biological consequences of ecosystem fragmentation. *Conservation Biology* **5,** 18–32.

Sharma, O.P., Makkar, H.P.S. and Dawra, R.K. (1988) A review of the noxious plant *Lantana camara*. *Toxicon* **26,** 975–987.

Shearer, B., Crane, C.E. and Cochrane, A. (2004) Quantification of the susceptibility of the native flora of the South-West Botanical Province, Western Australia to *Phytophthora cinnamomi*. *Australian Journal of Botany* **52,** 435–443.

Shearer, B.L. and Tippett, J.T. (1989) *Jarrah Dieback: the Dynamics and Management of* Phytophthora cinnamomi *in the Jarrah (*Eucalyptus marginata*) Forest of South-western Australia.* Research Bulletin No. 3, Department of Conservation and Land Management, Perth.

Stone, C. (1999) Assessment and monitoring of decline and dieback of forest eucalypts in relation to ecologically sustainable forest management: a review with case study. *Australian Forestry* **62,** 51–58.

Stone, C. (2001) Reducing the impact of insect herbivory in eucalypt plantations through management of extrinsic influences on tree vigour. *Austral Ecology* **26,** 482–488.

Stone, C. (2005) Bell-miner-associated dieback at the tree crown scale: a multi-trophic process. *Australian Forestry* **68,** 237–241.

Stone, C. (in press) Comparison of leaf, tree and soil properties associated with *Eucalyptus saligna* in a moist sclerophyll forest exhibiting canopy dieback. *Austral Ecology*.

Stone, C., Spolc, D. and Urquhart, C.A. (1995) *Survey of Crown Dieback in Moist Hardwood Forests in the Central and Northern Regions of NSW State Forests (Psyllid/Bell Miner Research Programme).* Research Paper No. 28. Research Division, State Forests of NSW, Sydney.

Turner, J. and Lambert, M.J. (1986) Effects of forest harvesting nutrient removals on soil nutrient reserves. *Oecologica* **70,** 140–148.

Turton, S.M. and Freiburger, H.J. (1997) Edge and aspect effects on the microclimate of a small tropical forest remnant on the Atherton Tableland, northeastern Australia. In: Laurance, W.F. and Bierregaard, R.O.Jr (eds) *Tropical Forest Remnants: Ecology, Management and Conservation of Fragmented Communities.* University of Chicago Press, Chicago, pp. 45–54.

Vertessy, R.A., Watson, F.G.R. and O'Sullivan, S.K. (2001) Factors determining relations between stand age and catchment water balance in mountain ash forests. *Forest Ecology and Management* **143,** 13–26.

Wardell-Johnson, G. and Calver, M. (2005) Toward sustainable management: southern Africa's afromontane, and Western Australia's jarrah forests. In: Calver, M.C., Bigler-Cole, H., Bolton, G.C., Gaynor, A., Horwitz, P., Mills, J. and Wardell-Johnson G.W. (eds) *Towards a Forest Consciousness.* Millpress, Rotterdam, pp. 729–739.

Wardell-Johnson, G. and Nichols, O. (1991) Forest wildlife and habitat management in southwestern Australia: knowledge, research and direction. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*. The Royal Zoological Society of New South Wales, Mosman, pp. 161–192.

Wardell-Johnson, G., Calver, M., Saunders, D., Conroy, S. and Jones, B. (2004) Why the integration of demographic and site-based studies of disturbance is essential for the conservation of jarrah forest fauna. In: Lunney, D. (ed.) *Conservation of Australia's Forest Fauna*, 2nd edn. Royal Zoological Society of New South Wales, Mosman, pp. 394–417.

Wardell-Johnson, G., Stone, C., Recher, H. and Lynch A.J.J. (2005a) A review of eucalypt dieback associated with bell miner habitat in south-eastern Australia. *Australian Forestry* **68,** 231–236.

Wardell-Johnson, G.W., Stone, C., Recher, H. and Lynch, A.J.J. (2005b) A review of eucalypt dieback associated with bell miner habitat in south-eastern Australia. Project BMAD 01/04 Science Report. University of Queensland, Gatton, Queensland. Unpublished report.

Wardell-Johnson, G.W., Kanowski, J., Catterall, C.P., McKenna, S., Piper, S. and Lamb, D. (2005c) Rainforest timber plantations and the restoration of plant biodiversity in tropical and subtropical Australia. In: Erskine, P.D., Lamb, D. and Bristow, M. (eds) *Reforestation in the Tropics and Sub-tropics of Australia Using Rainforest Tree Species*. Rural Industries Research and Development Corporation, Canberra, and the Rainforest CRC, Cairns, Chapter 11, pp. 162–182.

Wardle, D.A., Walker, L.R. and Bardgett, R.D. (2004) Ecosystem properties and forest decline in contrasting long term chrono-sequences. *Science* **305,** 509–513.

Waring, R.H., Savage, T., Cromack, X. and Rose, C. (1992) Thinning and nitrogen fertilization in a grand fir stand infested with western spruce budworm. Part IV: An ecosystem management perspective. *Forest Science* **38,** 275–286.

Webb, L.J. (1956) The rape of the forests. In: Marshall, A.J. (ed.) *The Great Extermination. A Guide to Anglo-Australian Stupidity, Wickedness and Waste.* Heinemann, London, pp. 156–205.

Whelan, R. (1995) *The Ecology of Fire.* Cambridge University Press, Cambridge.

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

White, T.C.R. (1984) The abundance of invertebrate herbivores in relation to the availability of nitrogen in stressed plant foods. *Oecologia* **63B,** 90–105.

White, T.C.R. (1993) *The Inadequate Environment: Nitrogen and the Abundance of Animals.* Springer-Verlag, Berlin.

Wylie, F.R., Johnston, P.J.M. and Eisemann, R.L. (1993) *A Survey of Native Tree Dieback in Queensland.* Research paper No. 16. Queensland Department of Primary Industries, Forest Service, Brisbane.

Young, J.T. (1994) The future — effects of plant disease on society. *Journal of the Royal Society of Western Australia* **77,** 185–186.