

Forest canopy health and stand structure associated with bell miners (*Manorina melanophrys*) on the central coast of New South Wales

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Summary

Forest attributes including canopy health and stand structure were visually assessed to identify features commonly associated with the bell miner (*Manorina melanophrys*, Meliphagidae), a cooperatively breeding, insectivorous honeyeater endemic to south-eastern Australia. A stratified random sampling methodology, using a combination of SPOT5 satellite imagery and a 25-m pixel digital altitude model, was used to establish 130 circular plots 40 m in diameter within a 12 800 ha study area in the Watagan mountain range, central coast of New South Wales (NSW). In this study site, the presence of bell miners was significantly associated with unhealthy eucalypt crowns. This supports the proposition that a dieback syndrome known as bell-miner-associated dieback (BMAD) exists in central coastal forests of NSW. Our results also demonstrate a strong association of a sparse eucalypt canopy over a dense lower midstorey with the presence of bell miners. Altitude and fire frequency were negatively correlated with bell miners while the topographical wetness index was positively correlated with bell miners. Logistic regression was used to quantify the effects of a series of explanatory variables including tree species, forest structure variables and selected topographic variables. Although there were significant differences in the ranking of crown condition between eucalypt species, tree species was not selected in the final model. The final variables identified by the logistic regression for the presence of bell miners included sparse eucalypt overstorey cover, dense lower midstorey cover, the absence of young vigorous regrowth trees and higher values of the topographic wetness index. Based on the results of our survey we discuss practical options for managing the forest dieback syndrome associated with bell miners in the central coast region of NSW and an approach to mapping forests at risk from BMAD.

Keywords: forest health; forest management; canopy; structure; dieback; bell miners; New South Wales

Introduction

Bell miners (*Manorina melanophrys*, Meliphagidae) are honeyeaters endemic to south-eastern Australia, extending from Gympie (Queensland) to near Melbourne (Blakers *et al.* 1984). They form colonies consisting of numerous breeding pairs that

occupy overlapping foraging ranges that they share with non-breeding offspring and immigrants (Smith and Robertson 1978; Poiani 1993; Clarke and Fitz-Gerald 1994). The colony's territory is communally defended against interspecific competitors and predators, resulting in a significant reduction of avian diversity within the canopy stratum (Smith and Robertson 1978; Loyn *et al.* 1983; Poiani 1991; Clarke and Fitz-Gerald 1994). The bell miner colonies commonly inhabit stands of eucalypts located in foothills and gullies (Loyn 1987). Under mild conditions they can breed throughout the year but cold, wet winters impose breeding seasonality (Poiani 1993). Breeding is also reduced during periods of drought (Clarke and Heathcote 1990).

Forests reported as being suitable for bell miner colonisation are extensive but patchily distributed and floristically diverse (e.g. Pearce *et al.* 1995; Pearce and Minchin 2001). Most studies on bell miners report on the common structural features of sparse canopy cover with a dense understorey (e.g. Poiani 1993; Pearce *et al.* 1995; Higgins *et al.* 2001). Clarke (1988) reported that a dense understorey of native or exotic shrubs is the preferred habitat for nesting sites. Nests are usually concealed in thick, shrubby undergrowth and built about 2–5 m above the ground (Smith and Robertson 1978; Clark 1988). Poiani (1993) observed that the major cause of nest failure was predation on both eggs and nestlings. It is assumed that this preferred habitat facilitates cooperative defence of their territory from predators and competitors.

More controversial is the association of bell miner colonisation with crown decline of the eucalypts (Loyn *et al.* 1983; Stone 1996; 1999; 2005; Clarke and Schedvin 1999; Jurskis and Turner 2002; Ewen *et al.* 2003; Jurskis 2005; Wardell-Johnson and Lynch 2005; Dare *et al.* 2007). That is, whether crown decline is in fact commonly associated with bell miners, and if so whether this is an effect of bell miner habitation or just an indicator of habitat suitability. Several studies have demonstrated that bell miner behaviour results in elevated psyllid populations (Loyn *et al.* 1983; Stone 1996; Clarke and Schedvin 1999; Ewen *et al.* 2003). Sustained feeding damage from these sap-sucking insects results in premature leaf death and defoliation (Stone 1996). Continued initiation and growth of replacement foliage depletes the tree's carbohydrate reserves (Bamber and Humphreys 1965) resulting in branch death and crown contraction. Affected

trees become weakened and more susceptible to other stressful agents such as wood borers and fungal pathogens (Moore 1962; Gerrettson-Cornell 1973; Old *et al.* 1990). If the bell miners vacate the affected stand, psyllid numbers significantly decrease (Loyn *et al.* 1983; Clarke and Schedvin 1999) and, if the trees have not become too debilitated, crown recovery can occur (Loyn *et al.* 1983; Stone 1996). Several authors, however, disagree with these findings and claim that bell miners move into stands already stressed from chronic abiotic processes that are presenting symptoms of decline including epicormic foliage which sustain elevated populations of herbivorous insects (Jurskis and Turner 2002; Jurskis 2005; Turner and Lambert 2005).

The aim of this survey was to confirm that the presence of bell miners is significantly associated with crown decline in forest types common to coastal New South Wales (NSW) forests (Forestry Commission of New South Wales 1989) and to identify the forest stand features strongly associated with bell miner colonisation. If we confirm that bell miners are significantly associated with canopy decline, then identification of other forest features also associated with this forest dieback syndrome may assist in formulating management options for affected forests in NSW (Wardell-Johnson and Lynch 2005). In addition, the identification of forest attributes associated with bell miners will contribute to mapping the actual and potential distribution of bell miners using remote sensing technologies.

Methods

Study site

Field plots were established in forests on the NSW central coast in an area we refer to as the Jilliby Catchment Study Area (JCSA) (the centre of the JCSA is at latitude 33°09'27.8"S, longitude 151°21'55.0"E). The JCSA is bounded by a rectangle of 8 km × 16 km (12 800 ha) made up of state forest (23%), national park (49%) and private or rural land (28%) (Fig. 1). Prior to mid-2003 the national park forest was part of the estate managed by Forests NSW. The existence of numerous bell miner colonies in forests throughout the JCSA has been known for decades and their distribution is thought to be increasing (State Forests of NSW 1995).

Terrain within the JCSA varies from steep and mountainous to relatively flat in the Jilliby creek valley. As part of the Watagan Range mountains, the topography is characterised by flat ridgelines, numerous sandstone cliffs, steep slopes and deeply fissured gullies (Murphy 1993). The geology is dominated by Hawkesbury and Narrabeen Group sandstones common within the Sydney Sedimentary Basin. The soils are generally acidic sandy loams with low to moderate fertility, and are highly erodible (Murphy 1993). The total annual rainfall for the JCSA in 2005 was 830 mm and in 2006 it was 775 mm. The mean total annual rainfall between 1966 and 2006 was 1039 mm (sd = 44 mm; Bureau of Meteorology 2007).

The JCSA has a wide array of vegetation communities that are highly diverse in both floristics and structure including rainforest, wet sclerophyll forest with a

mesic understorey, moist sclerophyll forest with a ferny or grassy understorey, and dry sclerophyll forest with grassy or xeric shrubby understorey (Binns 1996; Bell and Driscoll 2006). The distribution of vegetation communities in the JCSA is strongly linked to topography (i.e. aspect, slope and altitude) and soils, as well as to past forestry and rural practices (Murphy 1993; Binns 1996).

Most of the forests within the JCSA have been managed for integrated logging operations since the 1950s. No areas within the JCSA were defined as old growth (State Forests of NSW 1995), although isolated inaccessible moist stands do occur and have not been disturbed since the early harvesting of cedar trees about 100 y ago. The JCSA has also been exposed to a complex fire history associated with wildfires and controlled hazard reduction and post-logging burning.

Sampling design

Sampling was based on a stratified random sample with strata defined using a combination of SPOT5 satellite imagery (10-m pixel resolution) and a 25-m pixel digital altitude model (DEM). The sample population was initially reduced by excluding areas with slopes greater than 25° and more than 250 m from a forest road or trail, using GIS software. The trail network in Watagan Mountains is extensive but there was sampling bias against locating plots on the escarpments because of safety concerns. The four SPOT5 bands were fused with the DEM and an unsupervised classification performed to produce four spectrally homogeneous strata classes. Candidate sampling locations were further reduced

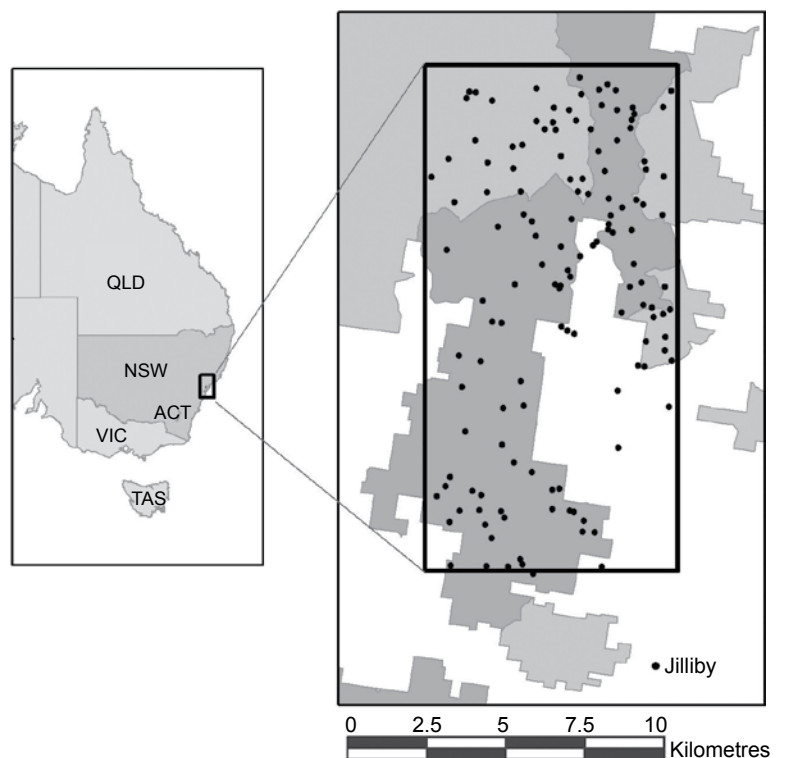


Figure 1. The location of the Jilliby Catchment Study Area and field plot distribution. The grey area represents forests managed by Forests NSW, the light grey area represents national park forests and the white area is private rural or forested land.

by selecting strata areas with a minimum size of 50 pixels (0.5 ha). Stratified random sampling was applied to allocate 30 plots to the four spectral strata (with an extra 10 plots in case of plot cancellations). A total of 130 plot coordinates were then generated for field assessment (Fig. 1). Altitude and topographic wetness index (NSW National Parks and Wildlife Service 1998) were calculated using a 10-m ground DEM derived from an airborne laser scanner (= LiDAR) (Leica Geosystems, Georgia, USA) covering the entire JCSA (R. Turner, Forests NSW, *pers. comm.*, August 2006). The wetness index provides an indication of the volume of water draining to each 10-m grid cell within the DEM adjusted according to the cell's ability to retain water due to slope. For each plot the mean value was calculated within a 20-m radius using ArcGIS 9.2 (ESRI, USA). The average altitude of the plots was 224 m (range = 34 m to 402 m).

The centre of each plot was located using a Trimble differential global positioning system (Trimble Navigation Limited) and pegged with a labelled steel post. The approximate perimeter of a circle of radius 20 m was then located and marked with spray paint. The presence or absence of bell miners was recorded for every plot. For each plot, the crown condition of every eucalypt above 'sapling' maturity was visually assessed using two visual scoring systems.

The first (referred to as Crown Condition 1) was based on visual estimates of the crown dieback ratio (Kile *et al.* 1981; Wardlaw 1989); epicormic index (Kile *et al.* 1981; Wardlaw 1989) and crown foliage transparency (US Department of Agriculture Forest Service 2002; Stone and Haywood 2006). The crown dieback ratio was estimated as the proportion of live crown area to the estimated original crown area, expressed as a percentage (to the nearest 10% category). The epicormic index was estimated as the proportion of current crown which is of epicormic origin (to the nearest 10% category), while crown foliage transparency was visually estimated (to the nearest 5% category) with the assistance of a crown density-foliage transparency card (US Department of Agriculture Forest Service 2002). Crown Condition 1 was calculated as:

$$\text{crown dieback ratio} + (100 - \text{epicormic index}) \\ + (100 - \text{crown foliage transparency}).$$

The second score (referred to as Crown Condition 2) was a modified version of that developed by Grimes (1978), based on categorical descriptions of crown size and shape; crown foliar density; presence of dead branches and leaf condition (Table 1) (Stone *et al.* 2003). The Crown Condition 2 value is the sum of scores obtained for each of the five crown attributes described in Table 1, that is crown size and shape, crown foliar density, dead branches, crown epicormic growth and foliar damage. In an earlier study, an association between psyllids, foliar damage and bell miners has been demonstrated at a site within the JCSA (Stone 1996) and hence, apart from a visual scoring of foliar damage (Table 1), no attempt was made to assess feeding damage from insects.

Visual evidence of logging (stumps) and fire (trunk blackening, charcoal) was recorded for each plot. Stand maturity of each plot was assessed by estimating the percentage contribution made by various tree growth stages (sapling, young vigorous, early mature, mature, overmature or dead), based on descriptions by Jacobs (1955) and Woodgate *et al.* (1994). The percentage area

of opaque crown cover for each vegetative stratum present in a plot (i.e. overstorey; upper midstorey (about 7–20 m in height), lower midstorey (about < 7 m in height), ground cover and bare ground) was visually estimated and scored into one of four broad categories; 0–25%, 26–50%, 51–75%, 76–100%. An estimate of the average height of each identified stratum was measured using a Vertex laser hypsometer. In addition to a census of all plant species in each plot, the three plant species most abundant in each stratum were recorded.

Logging and fire history

Logging and fire history records dating back to 1970 for a total of 52 Forests NSW land management units (= compartments) located within the JCSA, including the forested land transferred to National Parks in 2003, were accessed in several district offices. All the harvesting plans and fire records were then examined and the relevant information (described below) collated. The final output was an Excel spreadsheet containing textural (aspatial) and spatial data pertaining to logging and fire events since 1970, and shapefiles showing the spatial location of logging and fire events where this information was available to digitise. From this data set we were able to extract the following silvicultural attributes for the compartment in which each plot was located:

- frequency of fire events since 1970
- total area burnt since 1970
- mean area burnt
- number of logging events (for pulpwood, quota logs, salvage logs, poles and piles) since 1970
- total accumulated wood volume (m³) extracted since 1970
- mean volume per logging event.

Data analysis

Contingency tables, stacked bar plots and simple scatter plots were used for exploratory data analysis (EDA), using Genstat statistical software (VSN International Ltd, UK). This analysis checked data for mistakes, identified the most relevant variables and determined the complexity and or the general nature of models to be taken into account in the next stage.

The presence or absence of dominant tree species was tabulated against the presence or absence of bell miners. Species were treated as explanatory variables and the presence or absence of bell miners as dependent variables in correspondence analysis. Correspondence analysis gives a visual summary (one-dimensional in this case) of the relationship among a set of qualitative variables. The resulting plot identifies the cluster of variables that are clearly associated. A qualitative dependent variable (presence or absence of bell miners) can also be projected onto the same axis to determine which clusters of explanatory variables are associated with the presence of bell miners (Greenacre 1993; Dohoo *et al.* 1997). Correspondence analysis was done using PROC CORRESP procedure in SAS version 9.3.

Biserial correlation was calculated for all the plot response variables (i.e. dominant overstorey species, compartment fire and logging history since 1970, altitude, wetness index, proportions of tree growth stages and proportional contribution of vegetation cover) with the presence or absence of bell miners.

Table 1. The crown attributes and scoring system used to derive Crown Condition 2, a visual, ground-based estimate of eucalypt crown condition assessed in 130 plots within the Jilliby Catchment Study Area^A

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

^AA Crown Condition 2 value is the sum of scores obtained for each of five crown attributes: i.e. crown size and shape; crown foliar density; dead branches; crown epicormic growth and foliar damage. A maximum score of 25 represents a very healthy, vigorous eucalypt crown.

This correlation is used when an interval variable is correlated with a dichotomous variable. SAS macro %BISERIAL was used for the estimation of biserial correlation. The standard errors for the biserial correlation were estimated using bootstrap analysis (Efron and Tibshirani 1996).

Logistic regression analysis was used to identify the variables that were related with the presence of bell miners in the 130 plots, using the PROC LOGISTIC procedure in SAS version 9.3. The logistic regression model used for fitting the binomial bell miner data is defined as:

$$\log\left(\frac{p}{1-p}\right) = \beta_0 + \sum_{i=1}^k \beta_i x_i,$$

where p is the probability that bell miners are present given the value of an explanatory variable x_i , and β_0 is the intercept and β_1 is the regression coefficient. With a large number of variables there is a danger of over-fitting the model. It is usually preferable to limit the predictor degrees of freedom offered to any model selection algorithm by selecting a priori a relatively small set of candidate variables based on ecological knowledge (e.g. Wintle *et al.* 2005). The environmental variables altitude and wetness index were significantly correlated, and so we removed altitude from the analysis based on our field experience and observations on the distribution of bell miners reported in the literature (e.g. Higgins *et al.* 2001). Austin (2002) advocates the retention of 'proximal' environmental variables (e.g. the topographical wetness index) over 'distal' variables (e.g. altitude) if they are

strongly correlated. This was the only instance where a variable was selected on this criterion. We also eliminated variables which had very low biserial correlations and which had only a few non-zero values. Variables were added to the model using a stepwise selection technique and the statistical significance of the additional variables was tested using a likelihood ratio test, until a final set of statistically significant explanatory variables was established. The fit of the logistic model was assessed using the regression diagnostic developed by Pregibon (1981). The INFLUENCE option in SAS was used to provide a display of the diagnostic values, allowing visual inspection. The 'negative twice the log likelihood' (-2LogL) is given for the model with and without the independent variables (intercept only). Substantial reduction in the two values indicates a good predictive model. Hosmer and Lemeshow (1980) goodness of fit statistics were also used to check for model fit. When the probability of this test is more than 0.05, a good fit is indicated. Individual effects of independent variables were tested using Wald Chi Square test. The percent concordant values were also determined; the higher the percentage of concordant pairs the better the predictive power of the model. K-fold cross validation was used for model validation, with the area under the relative characteristic curve (AUC) as the assessment statistic (Pearce and Ferrier 2000).

Results

The sampling design captured the complete range of broad forest types identified in previous floristic surveys within the Jilliby area (Binns 1996; Bell and Driscoll 2006). A total of 23 tree species were recorded, of which 13 species were either *Eucalyptus*, *Corymbia* or *Angophora* species. Eucalypt species dominated the overstorey of most plots. *Corymbia maculata* was the overstorey dominant at lower altitudes while *E. punctata*, *E. paniculata*, *E. pilularis* and *E. umbra* were common dominants at all altitudes and *E. sparsifolia* was generally restricted to upper slopes and ridgetops. The most common non-eucalypt overstorey species was *Syncarpia glomulifera* (turpentine). This tree species appeared not be affected by the presence of bell miners and possessed vigorous crowns except in the driest plots. For example, the crown condition attributes of crown dieback ratio, crown foliage transparency, crown shape and size and dead branches (Table 1) were all significantly different (i.e. associated with better crown health) for *S. glomulifera* compared to *Eucalyptus* in plots colonised by bell miners ($P < 0.05$, $n = 37$ and $n = 158$ respectively).

The forest stands ranged in height from about 17 m to 50 m. Rainforest was observed to be confined to lower-altitude sites sheltered from fire. Two types of rainforest were recorded in the plots: subtropical rainforest on the alluvial flats of Jilliby Creek and dry rainforest stands dominated by thickets of *Choricarpia leptopetala* and *Backhousia myrtifolia*. Rainforest species were predominantly recorded in the upper midstorey stratum. A discontinuous overstorey of eucalypts, often *E. saligna*, was present in both types of rainforest.

Of the 130 plots assessed, 37 were colonised by bell miners. The mean two crown condition visual assessment schemes were significantly correlated ($r_p = 0.90$; $P < 0.001$, $n = 130$), with the crown condition scores of eucalypts in plots with bell miners

compared to the scores of eucalypt crowns without bell miners significantly lower for both assessment schemes. (That is, Crown Condition 1 = 169 ± 57 and $n = 423$ trees in plots with bell miners compared to 239 ± 22 and $n = 1076$ trees in plots without bell miners ($P < 0.001$); Crown Condition 2 = 16.6 ± 1.9 and 19.2 ± 1.3 , $P < 0.001$ (mean \pm standard deviation and means compared using Cochran t test)). There were a few exceptions, however: for example, three plots had tree crowns in poor condition but no bell miners. Two of these plots were recorded as having unhealthy eucalypt crowns but were thought to be drought affected as they were located in very dry gullies. A third plot was in a recently logged stand of *Corymbia maculata* in which the crowns had been scorched by a post-logging fire. Two plots with bell miners had apparently healthy crowns (Crown Condition 1 > 220). These plots had a very open overstorey and dead stags, and were dominated by *Cissus* vines. The few trees that were present were not in the species cluster closely associated with bell miners, for example, *E. pilularis* (Fig. 2). Overall, the eucalypt species with the unhealthiest crowns were *E. saligna*; *E. paniculata* and *E. punctata*, while the eucalypt species with the healthiest crowns were *E. agglomerata*, *E. umbra*, *C. maculata* and *E. microcorys*. For example, the mean Crown Condition 1 (CC1) values for *E. saligna* was 201 (se = 4.7) and for *E. paniculata* mean CC1 was 202 (se = 6.0), compared to a mean CC1 of 246 (se = 0.66) for *E. agglomerata* and mean CC1 of 235 (se = 2.5) for *E. umbra*.

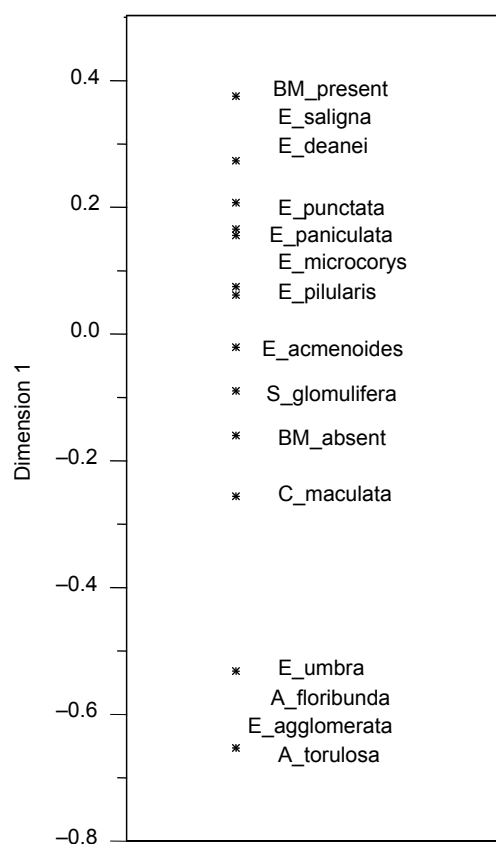


Figure 2. Plot illustrating the association of the most abundant overstorey species within the Jilliby Catchment Study Area with the presence or absence of bell miners using correspondence analysis. BM = bell miners; E = *Eucalyptus*; C = *Corymbia*; S = *Syncarpia*; A = *Allocasuarina*

The results of the correspondence analysis identified a cluster of tree species associated with the presence of bell miners, that is *E. saligna*, *E. deanei*, *E. punctata* and *E. paniculata*, and another cluster associated with the absence of bell miners, that is *Allocasuarina torulosa*, *E. agglomerata*, *Angophora floribunda* and *E. umbra* (Fig. 2). Most plots with the latter species tended to be on relatively dry sites (Bell and Driscoll 2006). A dense understorey of *Lantana camara* and or *Cissus antarctica* or *C. hypoglauca* was present in 22 of the 37 plots in which bell miners were present. A significant negative correlation was obtained for the visually estimated plot scores of vegetation cover for the overstorey and lower midstorey cover ($r_p = -0.35$, $P < 0.0001$, $n = 130$).

The only eucalypt growth stage that appeared to differ noticeably between plots with and without bell miners was the young vigorous class (Table 2). Young vigorous trees are still gaining height, their upper crown can be pointed or rounded in shape and the first-order branch angles are usually acute and uniform. This maturity class tended to be more common in plots without bell miners compared to plots colonised by bell miners, especially in the higher canopy cover classes associated with unthinned regrowth stands. Dead trees and overmature trees were not very different (Table 2), but this may have been due to the relatively small proportion of both standing dead trees and overmature trees per plot.

Logging activity has been extensive throughout the JSCA; evidence of prior logging (stumps) was seen in all but four of the plots while some visual evidence of fire was recorded in 122 plots. Caution is required in interpreting the silvicultural variables extracted from the compartment histories. At the compartment scale (mean compartment size in the JSCA = 219 ± 45.4 ha (sd)), each compartment had a fire event, on average, 7.2 times over the past 30 y, but most of these fires were patchy and associated with post-logging burning or controlled fuel reduction burns and with a bias towards the drier slopes and ridges. Larger wildfires were infrequent. The mean area for all fires recorded over this period was 237 ha (sd = ± 408 ha). The biserial correlation identified fire frequency as a notable correlation with the presence or absence of bell miners but none of the logging attributes were well correlated (Table 2).

The presence of bell miners was also negatively correlated to altitude and positively correlated to the topographical wetness index. The average altitude of all plots was 224 m (sd = ± 34.4 ; range = 34 m to 402 m) but only two of the 26 plots over 300 m were colonised by bell miners (304 m and 313 m respectively). Most plots with bell miners were below 250 m in altitude. Of all

the explanatory variables examined through biserial correlation analysis, the most significant correlations with the presence or absence of bell miners were related to stand structure — in particular, overstorey canopy cover and lower midstorey cover.

The logistic regression analysis (Table 3) identified overstorey canopy cover, lower midstorey cover, proportion of young vigorous trees and the wetness index as the four variables with

Table 2. Biserial correlation and bootstrap standard errors ($n = 1000$) of the plot-based explanatory variables (dominant overstorey species, compartment fire and logging history since 1970, wetness index; altitude, proportions of tree growth stages and proportional cover of vegetative strata) against the presence or absence of bell miners within the Jilliby Catchment Study Area

Variables	Biserial correlation	Bootstrap standard error
Young vigorous	-0.21	0.123
Early mature	0.06	0.129
Mature	0.11	0.131
Over mature	-0.15	0.104
Dead stag	0.11	0.133
Bare ground	0.001	0.125
Ground cover	0.01	0.113
Lower midstorey	0.49	0.117
Upper midstorey	-0.10	0.131
Overstorey	-0.52	0.094
Altitude	-0.26	0.104
Wetness index	0.22	0.112
Logging frequency	-0.10	0.111
Total wood volume	-0.02	0.122
Mean wood volume	0.04	0.119
Fire frequency	-0.23	0.119
Total area burnt	-0.15	0.124
Mean area burnt	-0.05	0.120
<i>Angophora floribunda</i>	-0.23	0.041
<i>Allocasuarina torulosa</i>	-0.10	0.030
<i>Corymbia maculata</i>	-0.14	0.105
<i>Eucalyptus acmenoides</i>	0.01	0.120
<i>Eucalyptus agglomerata</i>	-0.15	0.039
<i>Eucalyptus deanei</i>	0.19	0.124
<i>Eucalyptus microcorys</i>	0.05	0.128
<i>Eucalyptus paniculata</i>	0.13	0.125
<i>Eucalyptus pilularis</i>	0.11	0.120
<i>Eucalyptus punctata</i>	0.13	0.127
<i>Eucalyptus saligna</i>	0.24	0.131
<i>Eucalyptus umbra</i>	-0.27	0.070
<i>Syncarpia glomulifera</i>	-0.04	0.116

Table 3. Final logistic regression model identifying the optimal combination of explanatory variables predicting the presence of bell miners within the Jilliby Catchment Study Area

Variable	Estimate	Standard error	P	95% CI
Intercept	-4.82	2.75	0.080	
Lower midstorey	0.79	0.26	0.002	(1.34, 3.65)
Overstorey	-1.534	0.48	0.001	(0.09, 0.55)
Young vigorous	-0.314	0.14	0.028	(0.55, 0.97)
Wetness index	0.045	0.02	0.049	(1.0, 1.09)

Number of plots = 130; per cent concordant pairs = 83.4; the likelihood ratio value = 39.6 ($P < 0.0001$); Hosmer and Lemeshow goodness of fit statistic = 6.88 ($P = 0.55$)

strong effects on the likelihood of bell miners being present. Interestingly, although *E. saligna* was commonly associated with the presence of bell miners, it was not retained in the final model, nor were any of the logging variables. The likelihood ratio value (= 39.6) was highly significant ($P < 0.0001$) and Hosmer and Lemeshow goodness of fit statistic was 6.88 and $P = 0.55$. The probability value is > 0.05 ($P = 0.55$), indicating that the logistic model was an appropriate model for the presence or absence of bell miners. The percent concordant value of 83.4 suggests correct predictions for about 84% of the observations. Validation of the model was done by a ten-fold cross validation; we obtained a mean value of 0.84 with values ranging from 0.81 to 0.86.

Discussion

This survey supports and confirms several other studies in that the presence of bell miners is significantly associated with unhealthy eucalypt crowns (e.g. Loyn *et al.* 1983; Stone 1996; 2005; Clarke and Schedvin 1999; Ewen *et al.* 2003). In addition, our results also indicate that these unhealthy stands tend to possess a dense lower midstorey. This supports the observations of others (e.g. Higgins *et al.* 2001; Pearce and Minchin 2001) and the general assertion that vertical structure significantly influences insectivorous bird communities in eucalypt forests (e.g. Recher *et al.* 1985; Gilmore 1987). Jurskis (2005) advocates that bell miners are mainly found in undisturbed sites and although he does not specifically comment on the degree of canopy cover, he does mention the importance of understorey development associated with bell miners. If we assume the theory proposed by Specht (e.g. Specht 1983; Specht *et al.* 2006) applies to mature eucalypt forest communities, then in the absence of recent fire the sum of foliage projective covers of the overstorey and understorey strata remains constant and so the presence of an extensive dense understorey implies a relatively sparse overstorey.

Logging activity has historically been extensive throughout the JSCA but since the 1980s has been focused more towards the drier sites. Regeneration after logging on moist eucalypt sites along coastal NSW has long been recognised as difficult, especially on sites capable of supporting rainforest elements (Nicholson 1999). Logging opens up the overstorey; this favours eucalypt regeneration but if the site is also susceptible to invasion by aggressive mesic species (e.g. *Cissus* or *Lantana*) then the eucalypt regeneration can be suboptimal (King 1985). The results from our survey suggest that either preventing the establishment of, or subsequently removing, this mesic lower understorey would make the forest less at risk from bell miner colonisation. Plots supporting a sparse lower midstorey or the presence of an established upper midstorey stratum under an open sclerophyll forest were negatively associated with bell miners.

Soil disturbance and post-harvesting burning has long been advocated by foresters aiming to re-establish a sclerophyll overstorey (e.g. King 1985). Frequent, low-intensity fires maintain a non-shrubby lower understorey (e.g. Keith 1996), thus removing preferred nesting sites for the bell miners. On moister sites, if this fire regime is halted, re-invasion by the mesic understorey occurs and subsequent prescribed fires become more hazardous (e.g. Fernandes and Botelho 2003). Duggin and Gentle (1998)

concluded that increasing light availability promoted *L. camara* invasion in dry rainforests and their ecotones, and that shading was an effective strategy for preventing and controlling lantana. In this survey, young vigorous regrowth stands of *C. maculata* or *E. agglomerata* tended to have a relatively high stem density supporting little understorey and were not colonised by bell miners. Silvicultural practices that promote rapid overstorey regrowth and canopy closure are therefore an option for managing canopy decline associated with bell miners.

The plots covered the full compliment of forest types (Binns 1996) represented in the 12 800 ha JSCA, ranging from rainforest and wet mesic sclerophyll forests to dry grassy sclerophyll forests on ridgetops in the Watagan Mountain range. There was a significant difference in the ranking of crown condition of the dozen dominant species represented in these forest types — some tree species were positively associated with the presence bell miners while others significantly correlated with the absence of bell miners — but tree species was not a variable selected in the final logistic regression model. Numerous studies have demonstrated the importance of the abiotic environmental variables on species distribution. In an extensive floristic survey of the Morisset Forestry District, including much of the JSCA, Binns (1996) concluded that geology and fire age were the most important factors in determining overall floristic patterns. We found a significant association between the topographic wetness index and the presence of bell miners. In the literature it has been reported that bell miners commonly occur in foothill gullies and in open forests bordering creeks and gullies, sites which also tend to have higher wetness index values (e.g. Pearce and Minchin 2001).

Insect abundance in the unhealthy crowns was not assessed but high numbers of *Glycaspis* lerps and a small leaf miner (*Acrocercops* sp.) were frequently observed on leaves in the litter of affected plots. Sixteen species of psyllid have previously been identified on *E. saligna* foliage on trees located within the JSCA, with the most abundant psyllid in the presence of bell miners identified as *Glycaspis baileyi*. Woinarski *et al.* (1989) observed the psyllid preference of a range of insectivorous birds in a eucalypt forest near Bendigo, Victoria, and reported a common selection hierarchy of psyllid lerps, that is *Glycaspis*, *Lasiopsylla* then *Creiis* lerps. The *Glycaspis* lerps tended to have the highest concentration of soluble sugars. These psyllids are also phloem feeders and all insect phloem feeders require positive turgor pressure to extract available nitrogen (Huberty and Denno 2004). The fact that the presence of bell miner colonies was positively correlated to topographic wetness index may explain, in part, why *Glycaspis* populations are capable of building up to high and damaging densities on moister sites.

In a recent study near Melbourne, Dare *et al.* (2007) reported that at the time of initial occupation by bell miners two new sites did not have significantly elevated levels of psyllids compared with surrounding sites unoccupied by bell miners. After six months only one of the new sites had significantly elevated levels of psyllids. We suggest that for a stand to become affected by BMAD it requires site attributes capable of sustaining insect populations of damaging density, in addition to harbouring long-term occupancy by bell miners.

Mapping forests at risk from BMAD

Landscape mapping of bell miner distribution and the associated canopy decline is very difficult in mountainous topography. Expert interpretation either directly from an aircraft or from aerial photographs has been the traditional approach of attempting to map habitat and canopy health (Stone and Haywood 2006). Remote sensing technologies, however, are advancing rapidly. Recent studies have demonstrated the use of remote sensing to map spatial patterns of bird species indirectly through the mapping of associated habitat via image classification (e.g. St-Louis *et al.* 2006). LiDAR remote sensing was recently used to successfully measure several aspects of vegetation structure in a sclerophyll forest, including canopy cover and vertical stand structure, near Coffs Harbour, coastal NSW (Goodwin *et al.* 2006). We conclude that a range of remotely acquired digital imagery, in particular LiDAR, should be examined as to their potential contribution towards the development of a spatial model predicting canopy decline associated with the presence of bell miners.

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References

- Austin, M.P. (2002) Spatial prediction of species distribution: an interface between ecological theory and statistical modelling. *Ecological Modelling* **157**, 101–118.
- Bamber, R.K. and Humphreys, F.R. (1965) Variation in sapwood starch levels in some Australian forest species. *Australian Forestry* **29**, 15–23.
- Bell, S. and Driscoll, C. (2006) Vegetation mapping of Watagans National Park and Jilliby State Conservation Area. Summary report to Parks and Wildlife Division, Department of Environment and Conservation. Eastcoast Flora Survey, Kotara Fair, NSW.
- Binns, D. (1996) *Flora Survey Morisset Forestry District Central Region, New South Wales*. Morisset Forestry District EIS Supporting Document No. 3. State Forests of NSW Research Division, Sydney.
- Blakers, M., Davies, S.J.J.F., Reilly, P.N. and Royal Australasian Ornithologists Union (1984) *The Atlas of Australian Birds*. Melbourne University Press, Carlton, Victoria.
- Bureau of Meteorology (2007) A SILO product — longer-term rainfall observations. <http://www.bom.gov.au>; accessed 10 July 2007.
- Clarke, M.F. (1988) The reproductive behaviour of the bell miner *Manorina melanophrys*. *Emu* **88**, 88–100.
- Clarke, M.F. and Heathcote, C.F. (1990) Dispersal, survivorship and demography in co-operative breeding bell miner *Manorina melanophrys*. *Emu* **90**, 15–23.
- Clarke, M.F. and Fitz-Gerald, G.F. (1994) Spatial organisation of 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.
- Dare, A.J., McDonald, P.G. and Clarke, M.F. (2007) The ecological context and consequences of colonisation of a site by bell miners (*Manorina melanophrys*). *Wildlife Research* **34**, 616–623.
- Dohoo, I.R., Ducrot, C., Fourichon, C., Donald, A. and Hurnik, D. (1997) An overview of techniques for dealing with large numbers of independent variables in epidemiological studies. *Preventive Veterinary Medicine* **29**, 221–239.
- Duggin, J.A. and Gentle, C.B. (1998) Experimental evidence on the importance of disturbance intensity for invasion of *Lantana camara* L. in dry rainforest-open forest ecotones in north-eastern NSW, Australia. *Forest Ecology and Management* **109**, 279–292.
- Efron, B. and Tibshirani, R. (1996) Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Statistical Science* **1**, 54–77.
- Ewen, J.G., Crozier, R.H., Cassey, P., Ward-Smith, T., Painter, J.N., Robertson, R.J., Jones, D.A. and Clarke, M.F. (2003) Facultative control of offspring sex in the cooperatively breeding bell miner, *Manorina melanophrys*. *Behavioral Ecology* **14**, 157–164.
- Fernandes, P.M. and Botelho, H.S. (2003) A review of prescribed burning effectiveness in hazard reduction. *International Journal of Wildland Fire* **12**, 117–128.
- Forestry Commission of New South Wales (1989) *Forest Types in New South Wales*. Research Note No. 17. Forestry Commission NSW, Sydney.
- Gerretson-Cornell, L. (1973) The recovery of *Phytophthora cinnamomi* Rands from Ourimbah State Forest (Wyong, Newcastle District, New South Wales, Australia) and its pathogenicity to eucalypt seedlings under controlled conditions. *Phyton* **31**, 111–116.
- Gilmore, A.M. (1987) The influence of vegetation structure on the density of insectivorous birds. In: Keast, A., Recher, H.F., Ford, H. and Saunders, D. (eds) *Birds of Eucalypt Forests and Woodlands: Ecology, Conservation, Management*. Royal Australasian Ornithologists Union and Surrey Beatty and Sons, Sydney, pp. 21–31.
- Goodwin, N.R., Coops, N.C. and Culvenor, D.S. (2006) Assessment of forest structure with airborne LiDAR and the effects of platform altitude. *Remote Sensing of Environment* **103**, 140–152.
- Greenacre, M.J. (1993) *Correspondence Analysis in Practice*. Academic Press, London.
- Grimes, R.J. (1978) *Crown Assessment of Natural Spotted Gum (Eucalyptus maculata) Ironbark (E. fibrosa, E. drepanophylla) Forest*. Queensland Forest Service Technical Paper No. 7. Queensland Forest Service, Brisbane.
- Higgins, P.T., Peter, J.M. and Steele, W.K. (eds) (2001) *Handbook of Australian, New Zealand and Antarctic Birds, vol. 5. Tyrant-flycatchers to Chats*. Oxford University Press, Melbourne.
- Hosmer, D.W. and Lemeshow, S. (1980) A goodness-of-fit test for the multiple logistic regression model. *Communications in Statistics* **A10**, 1043–1069.
- Huberty, A.F. and Denno, R.F. (2004) Plant water stress and its consequences for herbivorous insects: a new synthesis. *Ecology* **85**, 1383–1398.
- Jacobs, M.R. (1955) *Growth habits of the Eucalypts*. Government Printer, Canberra.
- Jurskis, V. (2005) Eucalypt decline in Australia, and a general concept of tree decline and dieback: a review. *Forest Ecology and Management* **215**, 1–20.

- Jurskis, V. and Turner, J. (2002) Eucalypt dieback in eastern Australia: a simple model. *Australian Forestry* **65**, 81–92.
- Keith, D. (1996) Fire-driven extinction of plant populations: a synthesis of theory and review of evidence from Australian vegetation. *Proceedings of the Linnean Society of NSW* **116**, 37–78.
- Kile, G.A., Turnbull, C.R.A. and Podger, F.D. (1981) Effect of 'regrowth dieback' on some properties of *Eucalyptus obliqua* trees. *Australian Forest Research* **11**, 55–62.
- King, G.C. (1985) Natural regeneration in wet sclerophyll forest with an overstorey of *Eucalyptus microcorys*, *E. saligna* and *Lophostemon confertus*. *Australian Forestry* **48**, 54–62.
- Loyn, R.H. (1987) The bird that farms the dell. *Natural History* **96**, 54–60.
- Loyn, R.H., Runnalls, R.G., Forward, G.W. and Tyers, J. (1983) Territorial bell miners and other birds affecting populations of insect prey. *Science* **221**, 1411–1412.
- Moore, K.M. (1962) *Entomological Research on the Cause of Mortalities of Eucalyptus saligna Smith (Sydney blue gum)*. Research Note No. 11. Forestry Commission New South Wales, Sydney, 8 pp.
- Murphy, C.L. (1993) *Soil Landscapes of the Gosford-Lake Macquarie 1:100,000 Sheet Report*. NSW Department of Conservation and Land Management, Sydney.
- Nicholson, E. (1999) Winds of change for silvicultural practice in NSW native forests. *Australian Forestry* **62**, 223–235.
- NSW National Parks and Wildlife Service (1998) *Eden Fauna Modelling*. A report undertaken for the NSW CRA/RFA Steering Committee. NSW National Parks and Wildlife Service, Queanbeyan.
- Old, K.M., Gibbs, R., Craig, I., Myers, B.J. and Yuan, Z.Q. (1990) Effect of drought and defoliation on the susceptibility of eucalypts to cankers caused by *Endothia gyrosa* and *Botryosphaeria ribis*. *Australian Journal of Botany* **38**, 571–581.
- Pearce, J. and Ferrier, S. (2000) Evaluating the predictive performance of habitat models developed using logistic regression. *Ecological Modelling* **133**, 225–245.
- Pearce, J. and Minchin, P.R. (2001) Vegetation of the Yellingbo Nature Conservation Reserve and its relationship to the distribution of the helmeted honeyeater, bell miner and white-eared honeyeater. *Wildlife Research* **28**, 41–52.
- Pearce, J., Menkhorst, P. and Burgman, M.A. (1995) Niche overlap and competition for habitat between the helmeted honeyeater and the bell miner. *Wildlife Research* **22**, 633–646.
- Poiani, A. (1991) Anti-predator behaviour in the bell miner *Manorina melanophrys*. *Emu* **91**, 164–171.
- Poiani, A. (1993) Reproductive biology of the bell miner (*Manorina melanophrys*, Meliphagidae) at Healesville, south-eastern Victoria. *Wildlife Research* **20**, 579–598.
- Pregibon, D. (1981) Logistic regression diagnostics. *Annals of Statistics* **9**, 705–724.
- Recher, H.F., Holmes, R.T., Schulz, M., Shields, J. and Kavanagh, R. (1985) Foraging patterns of breeding birds in eucalypt forest and woodland of southeastern Australia. *Australian Journal of Ecology* **10**, 399–419.
- Smith, A.J. and Robertson, B.I. (1978) Social organization of bell miners. *Emu* **78**, 169–178.
- Specht, R.L. (1983) Foliage projective covers of overstorey and understorey strata of mature vegetation in Australia. *Australian Journal of Ecology* **8**, 433–439.
- Specht, R.L., Batianoff, G.N. and Reeves, R.D. (2006) Vegetation structure and biodiversity along the eucalypt forest to rainforest continuum on the serpentinite soil catena in a subhumid area of Central Queensland, Australia. *Austral Ecology* **32**, 394–407.
- St-Louis, V., Pidgeon, A.M., Radeloff, V.C., Hawbaker, T.J. and Clayton, M.K. (2006) High-resolution image texture as a predictor of bird species richness. *Remote Sensing of Environment* **105**, 299–312.
- State Forests of NSW (1995) *Morisset Forestry District Environmental Impact Statement Main Report*. State Forests of NSW, Sydney.
- Stone, C. (1996) The role of psyllids (Hemiptera:Psyllidae) and bell miners (*Manorina melanophrys*) in canopy dieback of Sydney blue gum (*Eucalyptus saligna* Sm.). *Australian Journal of Ecology* **21**, 450–458.
- Stone, C. (1999) Assessment and monitoring of decline and dieback of forest eucalypts in relation to ecologically sustainable forest management: a review with a case study. *Australian Forestry* **62**, 51–58.
- Stone, C. (2005) Bell-miner-associated dieback at the tree crown scale: a multi-trophic process. *Australian Forestry* **68**, 237–241.
- Stone, C. and Haywood, A. (2006) Assessing canopy health of native eucalypt forests. *Ecological Management and Restoration* **7**, S24–S30.
- Stone, C., Wardlaw, T., Floyd, R., Carnegie, A., Wylie, R. and de Little, D. (2003) Harmonisation of methods for the assessment and reporting of forest health in Australia — a starting point. *Australian Forestry* **66**, 233–245.
- Turner, J. and Lambert, M. (2005) Soil and nutrient processes related to eucalypt forest dieback. *Australian Forestry* **68**, 251–256.
- US Department of Agriculture Forest Service (2002) *Forest Inventory and Analysis: National Core Field Guide, 1: Field Data Collection Procedures for Phase 2 Plots*. Version 1.6. US Department of Agriculture Forest Service, Forest Inventory and Analysis, Washington, DC.
- Wardlaw, T.J. (1989) Management of Tasmanian forests affected by regrowth dieback. *New Zealand Journal of Forestry Science* **19**, 265–276.
- Wardell-Johnson, G. and Lynch, A.J.J. (2005) Landscape processes and eucalypt dieback associated with bell miner habitat in south-eastern Australia. *Australian Forestry* **68**, 242–250.
- Wintle, B.A., Elith, J. and Potts, J.M. (2005) Fauna habitat modelling and mapping: a review and case study in the Lower Hunter Central Coast region of NSW. *Austral Ecology* **30**, 719–728.
- Woinarski, J.C.Z., Cullen, J.M., Hull, C. and Nayudu, R. (1989) Lerp-feeding in birds: a smorgasbord experiment. *Australian Journal of Ecology* **14**, 227–234.
- Woodgate, P.W., Peel, W.D., Ritman, K.T., Coram, J.E., Brady, A., Rule, A.J. and Banks, J.C.G. (1994) *A Study of the Old-Growth Forests of East Gippsland*. Department of Conservation and Natural Resources, Victoria.