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Does the removal of *Lantana camara* influence eucalypt canopy health, soil nutrients site occupancy of a despotic species?

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ABSTRACT

Weed removal experiments provide strong evidence for weed impacts, validating management techniques and demonstrating the means by which biodiversity can be maintained. We examined the effects of removing Lantana (*Lantana camara*) through herbicide application in eucalypt-dominated sclerophyll forest and, then measured the response of soil carbon and nitrogen levels, tree canopy health and the density of Bell Miners (*Manorina melanophrys)* a bird species thought to amplify the negative impacts of Lantana on tree health. Four sites in northern New South Wales were monitored for 2.5 years. We measured Lantana health, (index of height, number of stems and leaves present), soil nutrients (nitrogen and carbon at two depths: 0–10 cm and 20–30 cm), Bell Miner density (using acoustic methods) and eucalypt canopy health (5 trees/quadrat) in six 50 × 50 m quadrats per site ($n = 24$; 12 treated, 12 untreated). Lantana foliage in treated quadrats was sprayed with glyphosate. Lantana showed significant reductions in health within 6 months of treatment and remained in a debilitated state compared to control quadrats for the duration of the project. Despite this, soil nutrients, Bell Miner density and canopy health did not differ between intact and treated quadrats for up to 2 years after treatment. The lack of impact on soil nutrient level or tree canopy health despite large changes in Lantana abundance in treatment sites was unexpected, and may indicate that Lantana is unimportant in shaping these measures. However, a more likely explanation is that longer term monitoring is required before the full impact of Lantana removal can be detected. The level of habitat modification following herbicide application was insufficient to stimulate relocation of Bell Miner colonies. Further investigation is required into how Lantana removal affects Bell Miner density, soil nutrient levels and canopy health in the medium to long term.

1. Introduction

Invasive plants threaten the integrity and function of numerous native ecosystems around the world. Competition for resources by invasive plants can directly affect ecosystem composition and structure (Wiser et al., 1998) and can also alter soil quality, water availability and fire regimes (Brooks et al., 2004). Invasive plants may adversely affect native plant species diversity by displacing mature vegetation or limiting juvenile recruitment (Yurkonis et al., 2005). Gooden et al. (2009) showed that invasion by Lantana (*Lantana camara*) reduced the establishment of *Eucalyptus* and native understorey species in wet schlerophyll forests. The mechanisms by which Lantana limits native species recruitment include allelopathy (Duggin and Gentle, 1998), and competition for light, nutrients and space (Sharma et al., 2003; Totland et al., 2005; Sharma and Raghubanshi, 2009; Carrion-Tacuri et al., 2011; Osunkoya and Perrett, 2011). Recruitment limitation may result in fewer resident juvenile plants in weed-invaded vegetation relative to non-invaded areas (Gooden et al., 2009; Sundaram and Hiremath, 2012).

Invasive plant removal studies provide strong evidence for invasive plant impacts on native species, since changes in species diversity and abundance following invasive plant removal can be directly measured (Turner and Virtue, 2006). Invasive plant impact mechanisms such as recruitment limitation can also be indicated by invasive plant removal studies by monitoring demographic changes in native species populations following weed control (D'Antonio et al., 1998). However, residual invader effects, such as altered soil nutrient concentrations, can influence the response of native species to weed removal (Mason et al., 2007).

Invasive plant control for biodiversity conservation aims to improve diversity by mitigating the adverse effects of invading plants, reducing their competitive effects and facilitating the

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rehabilitation of native vegetation (Mason and French, 2007). The removal of invasive plants has led to practical increases in species diversity in some areas, such as removal of the exotic perennial grass Coolatai grass (*Hyparrhenia hirta)* (Chejara, 2006). Positive outcomes following invasive plant removal are not guaranteed, however. Removal of Bridal Creeper (*Asparagus asparagoides)* led to plant biodiversity decline, due possibly to the influence of dead tubers below the surface on seedling establishment, the growth of a secondary invasive plant after removal and lack of suitable environmental conditions (Turner and Virtue, 2006). Additionally, invasive plant control can significantly disturb native communities, influencing the composition of regenerating native plants and potentially facilitating secondary plant invasion (Mason and French, 2007). Therefore, it is necessary to investigate the effects of the plant invader and the effects of its control on the factors that influence native vegetation growth such as soil nutrient pools, competition with canopy species and invasive plant influences on biodiversity where invasive plant removal has been advocated to promote community recovery.

We investigated the effects of Lantana invasion and treatment on wet sclerophyll forest where eucalypt dieback was present. Lantana is an exotic thicket-forming shrub that invades wet sclerophyll forest and rainforest margins in mainland eastern Australia (Swarbrick et al., 1998). Dense monospecific thickets often dominate the understorey, suggesting that the species reduces native vascular plant diversity (Duggin and Gentle, 1998). A positive feedback loop can occur where an invasive plant creates habitat favourable for its own regeneration (Buckley et al., 2007). Plants that prefer highly disturbed habitats with high light availability often generate positive feedback loops, including Lantana (Hiremath and Sundaram, 2005). The larger the canopy gap, the more persistent long-term invasions become (Totland et al., 2005). Originally from Central and South America, Lantana was introduced into Australia as an ornamental plant in the 1840s (DNRME 2004). Since then, Lantana has invaded 4 million hectares of forest and private land in eastern Australia (Parsons and Cuthbertson, 2001), and is listed as a Weed of National Significance (ARMCANZ, 2000).

Despite its negative effect on plant biodiversity, Lantana is thought to increase nesting habitat for the Bell Miner (*Manorina melanophrys*) which is suggested to be one of the causes of eucalypt dieback in wet sclerophyll forest in eastern Australia (Loyn et al., 1983). Lantana is part of a positive feedback loop, as it provides nesting habitat for the Bell Miner and is thought to increase soil nitrogen levels and *Eucalyptus* leaf nitrogen levels, which in turn make leaves more attractive to psyllids, herbivorous insects that produce a lerp, a waxy carbohydrate-rich covering that Bell Miners utilise as food (Haythorpe and McDonald, 2010). Bell Miners appear to require nesting habitat and lerp to inhabit an area (Dare et al., 2008a). Once Bell Miners colonise an area, an infestation of psyllids is thought to follow, as Bell Miners aggressively exclude all other avian species that prey on psyllids and lerp (Clarke and Schedvin, 1999; Dare et al., 2008b; Leseberg et al., 2014). Previous studies have shown that the regeneration and revegetation of native plant communities is possible through Lantana control (Macleay, 2004; Cummings et al., 2007; Gooden et al., 2009). However, field-based evidence linking Lantana, reduced understorey diversity, changes in soil nutrients, reduced canopy health and high Bell Miner density is scarce, discouraging effective Lantana and dieback management (Wardell-Johnson et al., 2005).

We assessed the responses of Lantana, canopy health, Bell Miner density, soil total carbon, soil total nitrogen and soil carbon–nitrogen ratio after the treatment of Lantana – infested wet sclerophyll forest in northern New South Wales. The effects of Lantana treatment on eucalypt dieback were determined by comparing the growth rate of Lantana, changes in soil chemistry, Bell Miner density and tree canopy health over a 2.5 – year period. Specifically, we asked, does Lantana treatment: (1) reduce Lantana health and if so over what time-scale; (2) affect soil chemistry properties (total nitrogen, total carbon and carbon–nitrogen ratio) and (3) influence Bell Miner density? We used an information theoretic approach to establish whether (4) ecological factors that appeared to be the primary influences on eucalypt canopy health.

2. Methods

2.1. Study area and habitat

The study was conducted in four sites in northern NSW, from May 2012 to October 2014: (1) Oxley Wild Rivers National Park (30°48.730′S; 152°04.052′E), near Armidale; (2) Kippara State Forest (31°10.918′S; 152°34.913′E), near Port Macquarie; (3) Toonumbar National Park (28°31.030′S; 152°46.129′E), and (4) Creek's Bend (28°34.012′S; 152°45.329′E), a private property, both near Kyogle. Creek's Bend and Toonumbar National Park have subtropical climates; Oxley Wild Rivers National Park has a temperate climate and Kippara State Forest is intermediate. The sites near Kyogle and Kippara State Forest have average temperatures ranging from 6.5 °C and 5.4 °C in winter, respectively to 29.9 °C and 27.8 °C in summer respectively. The corresponding temperatures in Oxley Wild Rivers National Park were −0.4 °C and 26.7 °C (Bureau of Meteorology, 2013). All sites experienced rainfall deficits in comparison to mean historical rainfall between October 2012 and January 2015 (Bureau of Meteorology, 2015).

Native vegetation in all sites was wet or dry sclerophyll forest, categorised by a tall open eucalypt canopy with an understorey of Lantana and various rainforest and sclerophyll shrub species and grasses. Sclerophyll forest in each study area had been extensively thinned or cleared by logging or for farming but had since been managed for restoration (Somerville et al., 2011). During periods of disturbance, Lantana had invaded the sites and had since became dominant in forest openings with an incomplete canopy cover.

Lantana treatment occurred at Creek's Bend in May 2012, followed by Toonumbar National Park in August 2012. The two other sites were treated in 2013: Oxley Wild Rivers National Park in February and Kippara State Forest in September. Monitoring was undertaken seasonally (i.e. at 3-monthly intervals) prior to and after treatment at each site. Treatments always occurred when plants were healthy with high numbers of leaves. Lantana responded in all sites with leaves dropping and plants dying.

2.2. Field methods

Before treatment, six 50 × 50 m quadrats (three treated with herbicide and three untreated) were measured at each site. As Bell Miner 'tink' calls can be monitored over 50 m, this distance was used to measure Bell Miner density (Lambert and McDonald, 2014). Quadrats contained Bell Miners, an understorey of Lantana and evidence of dieback in the canopy, such as reduction in leaf cover along with epicormic growth and branch death (Stone et al., 1995; Fig. 1). Control quadrats remained untreated throughout the study while treated quadrats were sprayed with glyphosate (Somerville et al., 2011). Quadrats were randomly placed throughout each site, at least 30 m apart in the forest interior and away from cleared land. All quadrats had a 30 m buffer zone of similar vegetation.

Within each quadrat, five points, each 25 m apart, were assessed, one in each of the four cardinal directions and another in the centre of the quadrat. As branch and foliage density are indicators of healthy Lantana growth (Totland et al., 2005), the occurrence of Lantana was recorded by noting the number of stems or

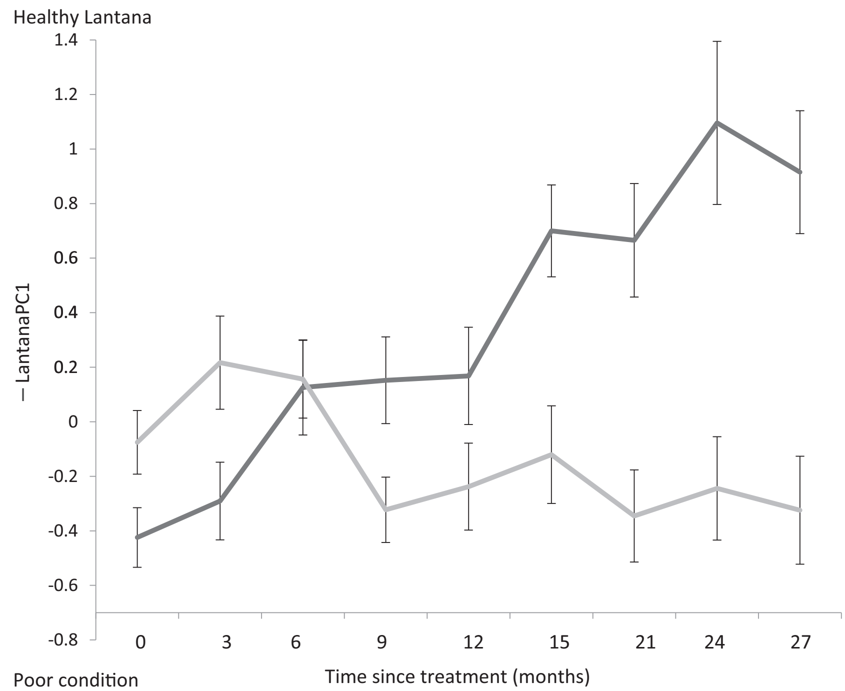

Fig. 1. Lantana health over time in relation to treatment (standardised across sites to time of spray). The black and grey lines indicate Lantana that was untreated and treated, respectively. High values of – LantanaPC1 indicate healthy Lantana and low values indicate poor conditions. Data are means ± 1 SE.

leaves touching a vertical pole at each point. To ensure that the same point was measured each time, we used a forestry pole (Telefix Telescopic height measuring pole 6 m, Telefix, Italy), attached to a camera tripod (Sherpa 600R, Velbon, China) levelled on the ground with gardening points placed at the end of the three legs. A metre ruler was used to score the number of Lantana stems and leaves touching the pole in each 20 cm interval from 0 to 6 m above the ground. Lantana height was recorded as the highest stem or leaf touching the pole. In the centre of the three gardening points, soil was collected before and at the end of the study (18–21 months after treatment) using a corer at depths of 0–10 cm and 20–30 cm.

Canopy health was scored using the system developed by Stone et al. (1995) considering the crown size, crown density, number of dead branches, crown epicormics growth and dead tree classification, photographed using a Olympus Tough TG-10 camera (Olympus Imaging Corporation, China). The density of Bell Miners was recorded at the centre of each quadrat, at 3-monthly intervals, to determine whether the treatment of Lantana affected the abundance of Bell Miners by recording sound for 10 min using a note taker, counting the number of calls and calculating the density using the formula in Lambert and McDonald (2014):

$$\#\ \text{birds in 50 m radius (n)} = \frac{\#\ \text{tink vocalisations per minute above 4530 U}}{2.9}$$

2.3. Soil sample preparation

The soil sampling depths were similar to or exceeded sampling depths used in previous investigations of *Eucalyptus* forest (e.g. Forrester et al., 2012). The soil samples were bulked in the laboratory to provide a single sample for each sampling depth in each quadrat. Soil samples were stored in sealed zip-lock bags and held in an insulated container of ice bricks to maintain a cool temperature during transit. All samples were transferred to a controlled-temperature facility at 4 °C within 6 h of field collection. All samples were weighed and dried in an oven at 40 °C for a week. After drying, samples were weighed again to determine total moisture content. Each sample was sieved (<2 mm) to remove coarse matter and then sieved to 0.5 mm for LECO analysis at the Environmental Analysis Laboratory at Southern Cross University (Lismore, NSW). Soil samples were analysed for total N and total C and, the C—N ratio calculated.

2.4. Statistical analysis

All statistical analyses were carried out in R version 3.1.0 (R Core Team, 2014) using generalised linear mixed models with a logit link function and binomial error distribution (GLMMs). Pearson's correlations showed that all Lantana variables (height, number of stems and number of leaves) were correlated. A principal components analysis (PCA) was applied to the matrix of Lantana variables to create orthogonal variables using the R package, Hmisc (Harrell, 2014). The interaction between time and treatment was used to test whether Lantana health varied with treatment over time with quadrats nested within site as a random effect. The importance of the interaction was determined using a likelihood ratio test (LRT) of significance following the removal of the term from the model. To determine whether there was an impact of treatment (and associated leaf and stem fall from sprayed Lantana plants) on soil total C, we examined total N and C—N ratio, before vs after treatment, in the R package lme4 (Bates et al., 2014). The two-way interaction between treatment and time was used to test for the effect of treatment on Lantana health; quadrat nested within site was modelled as a random effect. The importance of the interaction was tested with a LRT by dropping the interaction term from the models of each dependent variable. The interaction between time and treatment was used to test whether a difference in Bell Miner density emerged over time between treated and control quadrats. Quadrat nested within site was treated as a random effect.

The effects of season (winter, autumn, spring and summer), herbicide treatment, time (since Lantana was sprayed), canopy height (height of each canopy tree monitored for dieback) and Bell Miner density (number of birds detected within a 50 m radius) on canopy health were determined. Initial global models included all of the main effects and biologically relevant interactions. A candidate model set was then produced containing 19 models that had biologically relevant combinations of the above factors (Table 1). Akaike's Information Criterion (AIC_c) for small sample sizes was used for model selection, retaining models within an AIC_c value within 2 of the best-fit model, as data were not overdispersed (Burnham and Anderson, 2002). Multi-model inference was applied to the best-supported models to generate natural averages of coefficients using the R packages MuMIn (Barton, 2013) and AICcmodavg (Mazerolle, 2012).

3. Results

3.1. Effect of herbicide treatment on Lantana health

Since all three Lantana variables (height, number of stems and number of leaves) were correlated (number of Lantana stems and Lantana height, r = 0.56; number of Lantana leaves and Lantana height, r = 0.43; number of Lantana leaves and number of Lantana stems, r = 0.18; all $p < 0.001$). PCA was used to produce a linear combination that reflects the overall impact of herbicide application on Lantana health. The first component 'LantanaPC1' was the only one with an eigenvalue > 1, and explained 60.1% of the variation ($\lambda = 1.804$). When components were correlated with the raw data to determine factor loadings, increasing values of LantanaPC1 indicated decreasing Lantana height (−0.661), fewer stems (−0.573) and fewer leaves (−0.348). For ease of interpretation, LantanaPC1 was multiplied by −1 when plotted, so that higher values indicated healthy Lantana and lower values indicated Lantana in poor condition (Fig. 1).

Prior to treatment, Lantana in treated quadrats was in better condition than control quadrats (Fig. 1). Six months after treatment, Lantana in treated sites had declined, while Lantana in control sites had improved in health over the same period. The interaction between time and foliar herbicide application was significant for Lantana health (LantanaPC1, LRT, $\chi^2 1 = 51.39$, $p = 0.0001$).

Table 1
Explanatory models fitted to determine the most biologically relevant combinations of treatment*, time, season*, canopy height and bell miner density (*categorical variable) on tree canopy health. See methods for further explanation. Note that ':' indicates an interaction between two terms.

Canopy health models Model	Explanatory variables and interactions
M1	Treatment + time + season + canopy height + bell miner density + treatment:time + treatment:season + treatment:bell miner density + time:season + time:bell miner density + season:bell miner density + treatment:time:season
M2	Treatment + time + season + canopy height + bell miner density + treatment:time + treatment:season + treatment:bell miner density + time:season + time:bell miner density + season:bell miner density
M3	Treatment + time + season + canopy height + treatment:time + treatment:season + time:season + treatment:time:season
M4	Treatment + time + season + bell miner density + treatment:time + treatment:season + treatment:bell miner density + time:season + time:bell miner density + season:bell miner density + treatment:time:season
M5	Treatment + time + canopy height + bell miner density + treatment:time + treatment:bell miner density + time:bell miner density
M6	Treatment + season + canopy height + bell miner density + time: season + time:bell miner density + season:bell miner density
M7	Time + treatment + canopy height + bell miner density + treatment:bell miner density + time:treatment
M8	Time + treatment + bell miner density + treatment:bell miner density + time:treatment
M9	Time + treatment + time:treatment + season + canopy height + bell miner density
M10	Time + treatment + time:treatment + season + canopy height
M11	Time + treatment + time:treatment + canopy height
M12	Time + treatment + time:treatment + season
M13	Time + treatment + time:treatment
M14	Time + season
M15	Bell miner density + season
M16	Bell miner density + canopy height
M17	Season
M18	Time
M19	Canopy height
M20	Bell miner density

3.2. Effect of Lantana treatment on soil nutrients

While herbicide application impacted Lantana health and led to plants shedding leaves, and losing height and stem density, this did not measurably affect soil nutrient levels 24 months after treatment. In surface soil (0–10 cm), total N levels did not change before and after Lantana treatment ($\chi^2 1 = 0.624$, $p = 0.43$), nor did total C ($\chi^2 1 = 0.365$, $p = 0.55$), or the C—N ratio ($\chi^2 1 = 0.029$, $p = 0.86$). Furthermore, there was no change at 20–30 cm depth in total N ($\chi^2 1 = 0.089$, $p = 0.77$), total C ($\chi^2 1 = 0.002$, $p = 0.97$), or the C—N ratio ($\chi^2 1 = 0.254$, $p = 0.62$).

3.3. Effect of Lantana treatment on Bell Miner density

Although Lantana health declined in treated sites over time, Bell Miner density did not change over the corresponding period and in particular, in the 3–6 months after treatment (LRT, $\chi^2 1 = 1.915$, $p = 0.166$). Bell Miner colonies remained in the same locations for the duration of the study and none of the colonies relocated, regardless of whether they occupied treated or control sites.

3.4. Effect of ecological factors on tree canopy health

Canopy health declined over the course of the study (Fig. 2; Table 3). Six models of tree canopy health including the factors time since treatment, herbicide application, season, Bell Miner density, canopy height and their interactions, were among the models that were within 4 AIC_c units of the best-supported model, indicating some support for all of these (Table 3). AIC_c differences > 4 indicated other models tested had considerably less support (Burnham and Anderson, 2002). When the six models with some support were used to generate model-averaged coefficient estimates for each factor, all estimates were comparatively low (Table 2). The coefficient estimates and standard errors for Bell Miner density and the interaction between time and treatment had no effect on canopy health as these estimates overlapped with 0, indicating these factors had little biological relevance (Table 3). On the other hand, time and season were important in terms of canopy health. Canopy health declined over the 24 months after treatment but the effect was small (−0.18 ± 0.09%). Canopy health also increased with tree height (Table 3), but this effect was minor as well (0.13 ± 0.05%) and likely driven by broad differences in canopy height between sites, with Kippara State Forest having the tallest trees (32.9 ± 2.32 m) and Oxley Wild Rivers NP having the shortest (15.8 ± 1.93 m). Season had a small effect on canopy health, tree health peaking in autumn, declining in winter and improving in summer (Table 3; autumn 58.59 ± 0.96%; winter 56.13 ± 1.05%; spring 57.07 ± 1.02%; summer 58.27 ± 1.15%).

4. Discussion

Lantana health was impacted by glyphosate treatments with leaves falling off and negligible canes resprouting during the study.

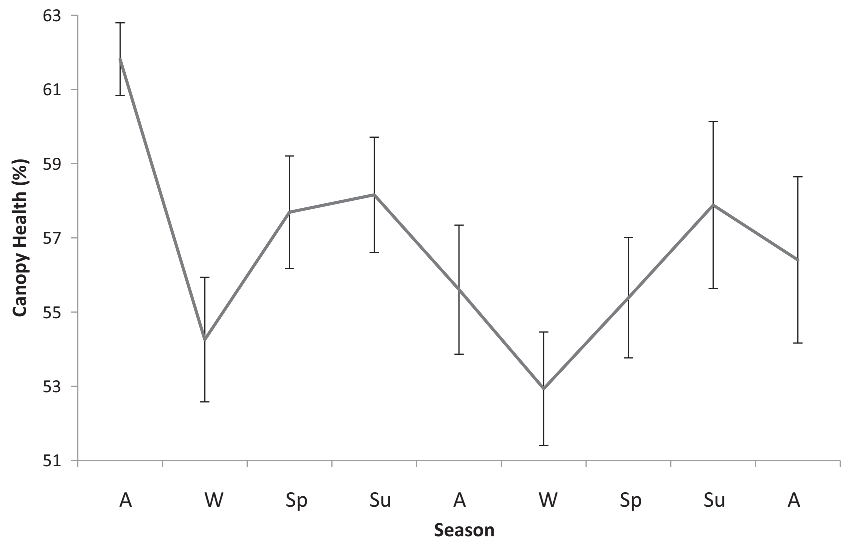

Fig. 2. The effect of time on canopy health percentage. Monitoring began in autumn (March–May) and was conducted seasonally.

Table 2
GLMMs were used to test the effect of Lantana condition and bell miner density on canopy health and arranged in order of increasing AIC_c. Models were constructed using logical, *a priori* combinations of the following variables: treatment, season, time since treatment, bell miner density and tree canopy height. Bold indicates the models within an AICc value of 1 in total to generate the natural averages of coefficients. AICc Akaike's Information Criterion corrected for small sample bias; ΔAICc, difference between model AICc and AICc of lowest model; *k*, number of parameters in the model; w_i, Akaike weight.

Explanatory variables	Model #	AICc	ΔAICc	*k*	w_i
Canopy height	**M19**	**9430.37**	**0.00**	**13**	**0.35**
Time + treatment + time: treatment + season + canopy height	**M10**	**9431.78**	**1.41**	**19**	**0.17**
Bell miner density + canopy height	**M16**	**9432.69**	**2.32**	**14**	**0.11**
Time + season	**M14**	**9432.83**	**2.46**	**16**	**0.10**
Time + treated + time: treatment + canopy height	**M11**	**9433.61**	**3.25**	**16**	**0.07**
Time + treatment + time: treatment + season + canopy height + bell miner density	**M9**	**9433.84**	**3.48**	**20**	**0.06**
Time	**M18**	**9434.46**	**4.09**	**13**	**0.04**
Time + treatment + time: treatment + season	M12	9436.16	5.79	18	0.02
Season	M17	9436.44	6.07	15	0.02
Bell miner density + season	M15	9437.13	6.76	16	0.01
Time + treatment + canopy height + bell miner density + treatment: bell miner density + time: treatment	M7	9437.46	7.09	18	0.01
Bell miner density	M20	9437.65	7.28	13	0.01
Treatment + time	M13	9437.69	7.32	15	0.01
Treatment + time + canopy height + bell miner density + treatment: time + treatment: bell miner density + time: bell miner density	M5	9438.25	7.88	19	0.01
Treatment + season + canopy height + bell miner density + time: season + time: bell miner density + season: bell miner density	M6	9438.54	8.17	25	0.01
Treatment + time + season + canopy height + treatment: time + treatment: season + time: season + treatment: time: season	M3	9441.51	11.14	28	0.00
Time + treatment + bell miner density + treatment: bell miner density + time: treatment	M8	9442.37	12.00	17	0.00
Treatment + time + season + canopy height + bell miner density + treatment: time + treatment: season + treatment: bell miner density + time: season + time: bell miner density + season: bell miner density	M2	9448.76	18.39	31	0.00
Treatment + time + season + canopy height + bell miner density + treatment: time + herbicide: season + treatment: bell miner density + time: season + time: bell miner density + season: bell miner density + treatment: time: season	M1	9451.63	21.26	34	0.00
Treatment + time + season + bell miner density + treatment: time + treatment: season + treatment: bell miner density + time: season + time: bell miner density + season: bell miner density + treatment: time: season	M4	9455.86	25.49	33	0.00

However, soil chemistry was not influenced by Lantana leaf fall, nor was the density of Bell Miners. Additionally, canopy health did not improve during the study but there an evident seasonal change with a peak in summer and autumn, declines in winter and improvements through spring and summer.

Our results demonstrate that the splatter gun technique based on a high concentration of glyphosate and developed by Somerville et al. (2011) can be effectively applied at a landscape scale. Measurable declines in Lantana health were found in treated quadrats, 6 months after application, and treated Lantana remained in poor condition compared to untreated Lantana up to 24 months post-treatment. A similar decline in Lantana health was recorded in a previous study (Somerville et al., 2011). Due to the listing of Lantana as a Weed of National Significance (Swarbrick et al., 1998), successful control throughout Australia is required to reduce the impact of Lantana on native ecosystems (Day et al., 2003). Lantana removal using the splatter gun technique is effective, costs less than hand pulling or applying basal bark herbicide (Somerville et al., 2011; Dohn et al., 2013), and is therefore the most cost-effective means for Lantana control.

Whilst the application of foliar glyphosate impacted Lantana in treated quadrats, this did not influence soil chemistry. We found no evidence that the levels of nitrogen or carbon in the top soil (0–10 cm) or at depth (20–30 cm) changed in the 18–21 months of the study following herbicide application. Lantana litter inputs have been suggested to alter soil N levels (Fan et al., 2009; Sharma and Raghubanshi, 2009). However, these studies compared areas invaded by Lantana with areas of native species cover to

Table 3
Model-averaged estimates of natural coefficients and standard errors (SE) for variables affecting canopy health (see Table 2 for selected models). Coefficient estimates ± 1 SE that did not overlap with 0, were considered influential (bold).

Explanatory variables	Estimate	SE	Relative variable importance
(intercept)	**61.06**	2.53	
Canopy height	**0.13**	**0.05**	**0.78**
Time	**−0.18**	**0.09**	**0.48**
Treatment	−1.61	1.67	0.35
Season			**0.33**
- Winter	**−3.42**	**1.31**	
- Summer	**−2.10**	**1.29**	
- Spring	−0.53	1.29	
Interaction between time and treatment	0.08	0.13	0.34
Bell miner density	0.02	0.09	0.11

determine the effect of Lantana leaf litter on soil nutrients. The present study compared soils from quadrats with treated and untreated Lantana. Our results suggest that Lantana in treated quadrats either still influenced soil chemistry via the decomposition of Lantana leaf litter 18–21 months after Lantana treatment, or that Lantana did not influence the soil chemistry of dieback-affected quadrats to begin with. These sites should be measured again once the Lantana leaf litter has completely decomposed to determine if the former explanation is correct. The timeframe for the decomposition of Lantana litter is unknown, so continued monitoring of Lantana treatment is required.

Bell Miners were not influenced by the decline in Lantana health in treated quadrats. There is little evidence that Bell Miner habitat choice is influenced by vegetation type (Lambert, 2015), so Lantana treatment may not reduce habitat quality in terms of either nesting or foraging habitat. Bell Miners have been observed nesting in various plant species, mainly in the understorey, and which vary greatly between colonies, implying that height and other factors such as nest microclimate are more important in nest site choice than plant species. A previous study found that nest concealment did not influence predation rates on nests (McDonald et al., 2009), so the effect of extreme climatic events may be reduced by nesting in the understorey (Clarke, 1988). A variety of plant species may therefore allow Bell Miners to reduce the climate impact of extreme events on nest success, leading to the difference in plant species chosen for nest sites between colonies (Lambert, 2015). Thus, if plant species are available that provide a suitable nesting microclimate other than Lantana, Lantana control may be ineffective in initiating Bell Miner relocation (Lambert et al., 2016).

Bell Miner density had no effect on tree canopy health in this study because bird numbers were invariant despite changes in canopy condition. This is contrary to previous studies that identified Bell Miners as the primary cause of decline in eucalypt canopy health in wet sclerophyll forest (Wardell-Johnson et al., 2005). Abandonment of a site by Bell Miners occurred at Creek's Bend after Lantana treatment using the splatter gun technique (Somerville et al., 2011), but vegetation structure differed between our sites and the Creek's Bend site (Lambert et al., 2016) that the colony abandoned. We found that Bell Miners did not occur in areas containing a midstorey with numerous stems and minimal understorey (Lambert et al., 2016). As the understorey decreased and the midstorey increased at Creek's Bend several years after treatment (Somerville et al., 2011; Lambert et al., 2016), the continued presence of Bell Miner colonies at the end of this study, 2.5 years after treatment, suggests that vegetation structure had not changed sufficiently to influence either nesting success or food resource availability. Furthermore, Bell Miners may nest in eucalypts 5 m above the ground regardless of understory condition (Lambert, 2015), and may also travel from nesting areas to food sources. Therefore, further investigation of Bell Miner foraging and nesting behaviour following Lantana treatment is required, particularly in terms of changes in nest site selection and foraging behaviour before and after treatment and the distance travelled from nesting sites to feeding sites.

Successful Lantana control in the present study did not influence canopy health, which instead was influenced to a small degree by season and time. Tree health varied with season, with increased epicormic growth in summer compared to winter, which is consistent with the seasonal growth of eucalypts (Cremer, 1972). Our results are consistent with the notion that dieback is caused by a variety of stresses (Jurskis, 2005), not just a single factor. If Lantana is treated but the leaf litter has not completely decomposed, elevated soil nutrient levels due to Lantana may persist beyond 21 months. A comparison of soil nutrients in adjacent areas with and without Lantana may be required to determine whether Lantana influences soil nutrients at these sites. If soil nutrients are still elevated 21 months after Lantana treatment, tree health may only start to improve once soil nutrient levels decline. Additionally, drought influences eucalypt health (Jurskis, 2008). A study in Mount Lindesay State Forest in northern NSW found negligible effects of Lantana removal on canopy health, but that tree condition increased with rainfall (St Clair, 2010). Other eucalypt stands showing symptoms of dieback have been found to recover with rainfall (Jurskis, 2008), but, New England dieback (a different form of eucalypt dieback), is exacerbated in high rainfall periods (Reid and Landsberg, 2000). A previous study of BMAD in Victoria found that drought influenced only some of the sites studied. Further research is required to disentangle the combinations of stressors causing BMAD in affected stands, as sites may respond differently to the combination of stresses and local land management activities and broader anthropogenic disturbance regime due to intrinsic differences between sites (Kasel, 1999).

In the present study, taller trees had slightly better canopy health than shorter trees. There were some differences in canopy tree species between sites, which means this result could be due to a tree species effect rather than a height effect per se. Drought may have influenced tree health, which declined over the study period as the rainfall deficit increased. As model selection suggested that canopy height was the most influential factor in explaining the variance in canopy health, further investigation is required to determine whether BMAD affects trees of the same species but of varying height differentially, to help determine the underlying causative mechanisms.

5. Conclusion

Foliar glyphosate application severely impacted Lantana health in four sites in NSW over a 21 month-period, although leafless Lantana canes were still present. The success of the splatter gun technique both in temperate and sub-tropical forest, suggests that managers can confidently apply this method to a broad climatic range of sites (Dohn et al., 2013). Lantana removal, however, did not influence the density of Bell Miner colonies. Soil nutrient pools had not changed 21 months after Lantana treatment, implying that the leaf litter was still decaying and releasing nutrients after treatment. Lantana presence may not be the only stress causing eucalypt dieback regardless of its impact on tree health. Further investigation is required to determine how Bell Miner density, soil nutrient pools and canopy health interact with Lantana over a longer time scale.

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