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# Successional changes in feeding activity by threatened cockatoos in revegetated mine sites

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**Abstract**

***Context.*** Provision of key habitat resources is essential for effectively managing species that have specific ecological requirements and occur in production landscapes. Threatened black cockatoos in the jarrah (*Eucalyptus marginata*) forest of Western Australia have a wide range, so their conservation requires support from all land tenures, not just reserves. Mining in the jarrah forest temporarily removes cockatoo feeding habitat, so it is important to understand how cockatoos exploit revegetated areas for food resources.

***Aims.*** We aimed to determine whether there were successional patterns in cockatoo feeding activity in revegetation aged from 4 to 23 years at three mine sites in the jarrah forest in south-western Australia.

***Methods.*** We surveyed 232 plots in revegetation to document (1) structural and floristic variation in vegetation across mine sites and revegetation ages, (2) differences in cockatoo feeding activity across mine sites and revegetation ages on the basis of feeding residues and (3) any edge effect reflecting preferential use of vegetation at the interior or exterior of mine pits. We also documented the frequency of occurrence of cockatoo food plants and feeding residues in 480 plots in unmined forest to compare with revegetated areas.

***Key results.*** Marri (*Corymbia calophylla*) and jarrah were commonly consumed in unmined forest and *Banksia* and *Hakea* species were also fed on to a lesser extent. Revegetated mine pits provided food within 4 years and continued to do so up until the oldest plots studied (23 years). The relative importance of food plants shifted from proteaceous species in young revegetation to myrtaceous species in intermediate to older revegetation. However, extent of feeding on myrtaceous species in older revegetation did not equate to feeding rates in unmined forest, with lower frequencies recorded in revegetation.

***Conclusions.*** Black cockatoos fed in revegetation at all three mine sites, despite variations in vegetation age, structure and floristics. Feeding on proteaceous and myrtaceous food plants occurred within 4 and 7 years of revegetation being established, respectively, indicating that some food resources are restored quickly after mining disturbance of the jarrah forest.

***Implications.*** Our results emphasise the importance of monitoring fauna recolonisation over appropriate time scales, to understand how successional processes in revegetation influence fauna population persistence in production landscapes.

**Additional keywords:** *Calyptorhynchus*, disturbance, feeding traces, jarrah forest, production landscape, restoration, revegetation, succession.

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## Introduction

Primary industries, such as agriculture, forestry and mining, disrupt ecosystems with the potential to clear habitat, alter hydrological processes, spread pathogens and degrade soils (Vitousek *et al*. 1997; Fischer *et al*. 2006; Gibbons and Lindenmayer 2007). However, production landscapes, where these primary industries occur, can play important roles in maintaining biodiversity and ecosystem resilience, provided they are managed appropriately (Fischer *et al.* 2006). Revegetation of cleared and disturbed areas can promote the persistence of fauna in production landscapes, but recolonisation of revegetated sites depends on the restoration of key resources, which may take decades, or centuries, to develop as revegetation matures (Munro *et al.* 2007; Nichols and Grant 2007). Studies of the success of revegetation need to consider the activity of fauna in revegetated sites over long time frames (Vesk *et al.* 2008; Gould 2011). Understanding how the availability of key resources changes as revegetation ages is essential for effectively managing species with specific habitat requirements.

Habitat loss is a major threat to the survival of the three black cockatoos endemic to south-western Australia (the forest red-tailed black cockatoo (*Calyptorhynchus banksii naso*; FRTBC), Carnaby's cockatoo (*Calyptorhynchus latirostris*; CBC), and Baudin's cockatoo (*Calyptorhynchus baudinii*; BBC) (Chapman 2008; Garnett *et al.* 2011; Department of Environment 2012; Johnstone *et al.* 2013*a*, 2013*b*). All three species of cockatoo are listed as threatened under the *Commonwealth Environment Protection and Biodiversity Conservation Act* 1999, whereas CBC and BBC are classified as Endangered in the IUCN Red List (Birdlife International 2013*a*, 2013*b*). Studies of the cockatoos' response to clearing and subsequent revegetation are important if population declines are to be halted or reversed.

All three species of cockatoo forage and nest in the jarrah (*Eucalyptus marginata*) forest (Johnstone and Kirkby 2008; Johnstone *et al.* 2013*a*), which is the largest contiguous forest in south-western Australia and is managed for mining, timber harvesting and water catchments, as well as biodiversity conservation (Conservation Commission of Western Australia 2012). Extensive agricultural clearing has reduced the distribution of jarrah from an estimated 5.3 million ha (mapped in Lane Poole 1920) to ~3.3 million ha (Dell and Havel 1989). Timber harvesting and mining in the jarrah forest involve clearing and modification of habitat, followed by regrowth or revegetation. Approximately 800 000 ha of the jarrah and wandoo (*Eucalyptus wandoo*) forests are available for logging and 45% of State Forest and timber reserves are covered by State mining agreements or approved mining leases (Conservation Commission of Western Australia 2012). Approximately 1000 ha of native forest is cleared for mining (principally for bauxite, coal and gold) annually. The long-term cumulative impacts of mining are expected to be clearing of 83 000 ha (7% of State forest area) and the fragmentation of 337 000 ha (28% of State forest area) over the next 30 or more years (Conservation Commission of Western Australia 2012).

Mining operations in the jarrah forest use similar revegetation procedures and aim to re-establish a jarrah forest ecosystem over time (Rayner *et al.* 1996; Koch 2007). In the early stages, the structure and floristics of revegetated pits are distinct from surrounding native forest, with low canopies, high stem densities and dense leguminous or proteaceous understoreys. They come to resemble unmined forest more closely as the vegetation ages, a canopy of eucalypts forms and fire and silvicultural treatments are applied (Koch and Hobbs 2007). Lee *et al.* (2010, 2013*a*, 2013*b*) used feeding residues (e.g. chewed eucalypt fruits) to document the use of 7–14-year-old revegetated mine pits by black cockatoos at the large, open-cut Newmont Boddington Gold mine (NBG) in the jarrah forest near Boddington, Western Australia. All three species of cockatoo fed in the pits within 8 years of revegetation. CBC ate seeds from the proteaceous genera *Banksia* and *Hakea*, whereas BBC and FRTBC ate seeds from the myrtaceous canopy species marri (*Corymbia calophylla*). The relative abundance of cockatoo food resources is likely to change as revegetation matures (Norman *et al.* 2006), yet the significance of this for feeding by black cockatoos is not understood. Also, mining landscapes in the jarrah forest generally consist of a mosaic of cleared, revegetated and unmined areas, leading to potential edge effects on fauna populations (Craig *et al.* 2015). Edge effects may influence cockatoo feeding activity through differences in food availability between the interior and exterior of revegetated mining pits (e.g. Harris and Reed 2002; Morris *et al.* 2010), improved accessibility to dense vegetation at the edges, or differences in predation risk between the interior and exterior of pits (e.g. Wolf and Batzli 2004; Morrison 2011). How cockatoo feeding activity or habitat is influenced by such mechanisms remains poorly understood (but see Lee *et al.* 2013*b*). Given the extent of habitat modification in the jarrah forest, understanding cockatoo feeding ecology in revegetated areas and their response to revegetation edges will be increasingly important for managing their populations.

We sought to address these knowledge gaps by comparing the results of Lee *et al.* (2010, 2013*a*, 2013*b*) to additional data on feeding activity by black cockatoos in revegetated areas and unmined forest at two other mine sites in the jarrah forest, namely, the Huntly mine of Alcoa of Australia Ltd (hereafter AA) and the Boddington Bauxite Mine of BHP Billiton Worsley Alumina (hereafter BBM). We tested whether there are successional patterns in cockatoo feeding activity in revegetation aged from 4 to 23 years, by documenting (1) structural and floristic variation in vegetation across mine sites and revegetation ages, (2) differences in cockatoo feeding activity across mine sites and revegetation ages on the basis of feeding residues and (3) any edge effect reflecting preferential use of vegetation at the interior or exterior of revegetated mine pits. We also documented the frequency of occurrence of cockatoo food plants and feeding residues in unmined forest at all three sites, to compare to revegetated areas.

## Materials and methods

### *Study areas*

The three study sites are located in the jarrah forest of south-western Australia (Fig. 1), where the climate is Mediterranean, with cool, wet winters, and warm, dry summers (Charles *et al.* 2010). The AA mine is a surface bauxite mine located 10 km north of Dwellingup, in the western jarrah forest. Mean annual rainfall at Dwellingup is 1242 mm (Bureau of Meteorology 2014). The BBM mine is a surface bauxite mine 15 km south of Boddington and the NBG mine is an open-cut gold and copper mine 17 km north-west of Boddington, both being in the eastern margin of the jarrah forest. Mean annual rainfall at Boddington is 668 mm (Bureau of Meteorology 2014).

The three study areas all consist of a mosaic of unmined forest and revegetated mined areas of varying ages. Revegetated mining pits at AA are generally between 2 and 30 ha in size, and 40–50% of the landscape is typically cleared, mined and then revegetated (Koch 2007). Following mining, pits at AA are revegetated by reseeding with jarrah, marri and 76–111 understorey species, and by hand-planting species that do not return from seeding (Koch 2007). For further details of the mining and revegetation procedures used, see Grant and Koch (2007) and Koch (2007). The mining and revegetation process at BBM is similar to that at AA, although specific details on seed mixes are not available.

The NBG mine consists of two large (i.e. several km wide) and deep (<1 km) pits, and 50 smaller 'satellite' pits that have been revegetated, and total ~190 ha in area (Rayner *et al.* 1996; Lee *et al.* 2013*b*). A large area at NBG is also dedicated to residue disposal and waste rock dumps. Revegetation of the satellite pits at NBG was undertaken according to the methods described in Rayner *et al.* (1996) and is similar to those used at AA. Seed mixes included jarrah, marri and wandoo as canopy-forming species, and a range of understorey species, including *Banksia*, *Hakea* and *Allocasuarina* spp.

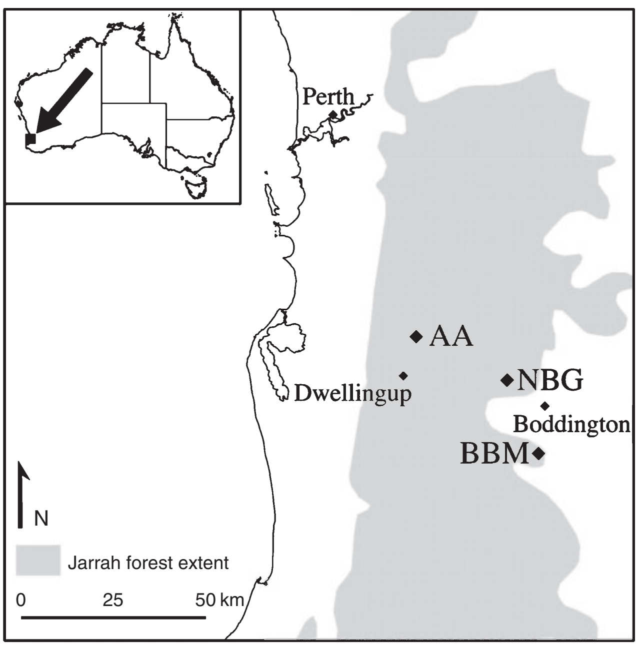


**Fig. 1.** The location of the three study sites in south-western Australia. AA, Alcoa of Australia Ltd Huntly bauxite mine; BBM, BHP Billiton Worsley Alumina Boddington Bauxite Mine; NBG, Newmont Boddington Gold mine.

### *Unmined forest plots*

At each study site, plot-based sampling was used in both unmined forest and revegetated areas to obtain floristic and structural vegetation data and to describe spatial and floristic patterns in cockatoo feeding activity. To provide a reference against which revegetated areas could be compared, we recorded the presence of cockatoo food plants and feeding residues in 25 × 25-m plots in unmined forest at each site (NBG, $n = 425$ plots; BBM, $n = 35$; AA, $n = 20$). To effectively sample feeding residues in unmined forest, these plots were larger than those used in revegetation because unmined forest has a much lower density of potential food plants. Potential food-plant species were *Banksia dallaneyi*/*nivea*, *B. grandis*, *B. sessilis*, *B. squarrosa*, *Hakea amplexicaulis*, *H. lissocarpha*, *H. prostrata*, *H. trifurcata*, *H. undulata*, marri, jarrah, sheoak (*Allocasuarina fraseriana*), *Persoonia longifolia* and wandoo. We also recorded the presence of cockatoo feeding residues within the plots (see *Feeding residues* below). Plots in unmined forest at BBM and AA were surveyed in May and June 2010 respectively, whereas plots at NBG were surveyed in the period October 2009 – March 2010. Although unmined forest plots at NBG were surveyed at a time of the year different from that for the other two sites, this is unlikely to have influenced the results because residues from both recent and past feeding events were measured at all sites and we present only presence/absence data for feeding in unmined forest plots.

### *Revegetated mining pits*

We sampled interior and exterior plots in revegetated mining pits to examine potential edge effects related to vegetation structure or feeding activity. Interior plots (10 × 10 m) were located ≥25 m from the edge of revegetated pits and exterior plots (20 × 5 m) ran along the pit edge because we did not want exterior plots to extend too far from the edge. Some plots on the pit edge at BBM and AA were 10 × 10 m (Fig. 2). All plots were separated by ≥50 m.

In July 2009, we surveyed 90 plots at NBG that were revegetated between 1996 and 2002 (7–13 years old at the time of sampling), of which half were exterior plots (20 × 5 m) and half were interior plots (10 × 10 m; Fig. 2). These are the same data as reported as the first sampling period in Lee *et al.* (2013*b*). In May 2010, we surveyed 82 plots at BBM of which half were revegetated between 1987 and 1992 (18–23 years old) and the other half between 1997 and 2004 (6–13 years old). We surveyed 20 interior plots (10 × 10 m) and 20 exterior plots

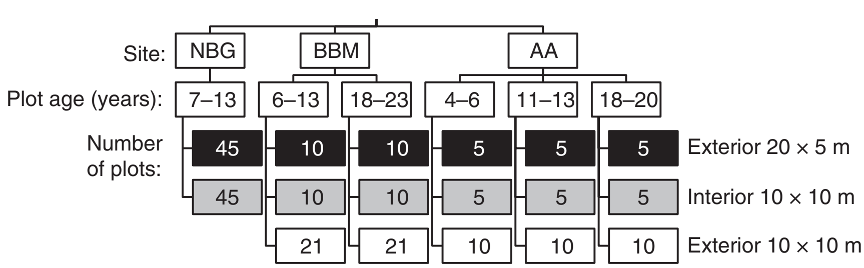


**Fig. 2.** Study design for plot-based sampling at Newmont Boddington Gold mine (NBG), BHP Billiton Worsley Alumina Boddington Bauxite Mine (BBM) and Alcoa of Australia Ltd Huntly bauxite mine (AA). Plot age at time of sampling and number of plots at each site is given.

(20 × 5 m) to allow for testing of edge effects. The remaining 42 plots were exterior plots (10 × 10 m). In June 2010, we surveyed 60 plots at AA, 20 that were revegetated between 1990 and 1992 (18–20 years old), 20 revegetated between 1997 and 1999 (11–13 years old), and 20 revegetated between 2004 and 2006 (4–6 years old). In each AA age class, there were five interior plots (10 × 10 m) and five exterior plots (20 × 5 m). The remaining 10 plots in each age class were exterior plots (10 × 10 m; Fig. 2).

### *Revegetation structure and floristics*

We sampled vegetation floristics and structure within each revegetation plot to compare these features among revegetation ages, mine sites and plot locations (interior or exterior). Floristics were recorded as the number of species present known to be food plants of the three study species (Table 1), on the basis of Saunders (1974*a*, 1974*b*, 1980), Johnstone and Storr (1998), Johnstone and Kirkby (1999), Johnstone *et al*. (2013*b*) and Lee *et al*. (2013*a*). To quantify vegetation structure, we measured canopy cover, canopy height and understorey height, and counted stem densities of plant species that are a common food resource for black cockatoos (*Banksia* spp., *Hakea* spp., marri and jarrah; Table 1). Measurements of canopy cover were taken using a 10-m point-intercept transect situated within each sampling plot. For 10 × 10-m plots, we positioned the transect running through the middle of the plot and parallel to the pit edge from one side to the other. For 20 × 5-m plots, we positioned the transect parallel to the long axis, and in the middle of the plot, so that the transect was 2.5 m from the long, and 5 m from the short axis of the plot. For measurements of stem density, canopy height and understorey height, we considered a plant a 'stem' only if it was ≥0.5 m tall and at least half the bole was within plot boundaries.

### *Feeding residues*

We used feeding residues to investigate patterns in feeding activity across revegetation ages and mine sites, following the methods described by Lee *et al*. (2013*b*). Feeding residues were (1) cracked or split proteaceous seed pods or fruits (*Hakea* and *Persoonia* spp.), (2) cut proteaceous branches (*Banksia* and *Hakea* spp.) and (3) chewed fruit husks of large trees (marri, jarrah and sheoak). Given the difficulties of attributing all residues exclusively to different black cockatoo species, we present data collectively as 'black cockatoo feeding'.

Residues were counted in sampling plots by searching the ground beneath potential food plants (≥0.5 m tall). We counted all residues beneath the canopy of each food plant, including any sections of the canopy extending beyond plot boundaries. Where the canopy of a stem within plots overlapped that of a plant outside plots, we divided the residues equally. If litter had fallen onto residues, we removed it before identifying and counting residues. Counts of residues from all stems of each food plant species were summed for each plot. At NBG, husk residues were too abundant to count in two plots, so the total was estimated from the depth and area covered. At BBM and AA, revegetation plots were checked for feeding residues once each in May 2010 and June 2010, respectively. At NBG, revegetation plots were checked for feeding residues and cleared of residues on three occasions (Lee *et al*. 2013*b*), but we present data only for July 2009, the first sampling period. Residues had accumulated over an indefinite period of time before sampling, but we have no reason to suspect substantial differences in residue degradation rates among the three study sites.

### *Statistical analyses*

To describe patterns in cockatoo food-plant availability and feeding activity, we present bar plots indicating the percentage of unmined forest and revegetation plots at each site that (1) contained cockatoo food-plant species and (2) contained evidence of feeding on those species. We used general linear models (GLMs) to test for differences in vegetation structure and feeding activity between the two types of exterior plots at BBM and AA (10 × 10 or 20 × 5 m, $n = 107$ plots). Following non-significant results (Table S1, available as Supplementary Material for this paper), we pooled data from the two types for further tests. One variable (*Banksia* stem density) was significantly different between the two types of exterior plots (Table S1), so we excluded the 10 × 10-m exterior plots from the test of edge effects on *Banksia* stem density ($n = 160$ plots).

We used GLMs to test for any effect of plot age (number of years since revegetation), location (interior or exterior), site (three levels) and the interaction between age and site, on the vegetation-structure and floristics variables ($n = 232$ plots). The dependent variables were the stem density of food-plant species (*Banksia* spp., *Hakea* spp., jarrah and marri), canopy cover, canopy height, understorey height and species richness of potential food plants in plots (Table 1). We similarly used GLMs to test the effect of plot age, location, site and the

**Table 1. Structural and floristic variables measured in revegetation plots**

| Variable | Definition |
|---|---|
| Stem density | Number of stems (≥0.5 m height) of feed species (*Banksia* spp., *Hakea* spp., marri (*Corymbia calophylla*) and jarrah (*Eucalyptus marginata*)). |
| Canopy cover | Measured at 1-m intervals along point-intercept transect using an optical densitometer ($n = 10$ measurements per plot). Results were recorded as 1 (fully covered), 0.5 (partially covered) and 0 (no cover). The 10 measurements were summed to give single canopy-cover values between 0 and 10 for plots. |
| Canopy height | Mean height of stems from canopy-forming species (≥0.5 m height). We regarded plants of the genera *Eucalyptus*, *Corymbia*, *Allocasuarina* and *Acacia* as canopy-forming species. Measured using a Levy pole or a digital hypsometer. |
| Understorey height | Mean height of plants from genera other than those regarded as canopy-forming (≥0.5 m height). Measured using a Levy pole. |
| Species richness of potential food plants | Number of species present that are known food plants of the three study species (*Banksia dallaneyi*/*nivea*, *B. grandis*, *B. sessilis*, *B. squarrosa*, *Hakea amplexicaulis*, *H. lissocarpha*, *H. prostrata*, *H. trifurcata*, *H. undulata*, marri, jarrah, wandoo (*E. wandoo*), sheoak (*Allocasuarina fraseriana*) and *Persoonia longifolia*). |

interaction between age and site on the presence of cockatoo feeding residues within plots (logistic regression) and on the numbers of *Banksia* spp., *Hakea* spp., jarrah and marri feeding residues in plots ($n = 232$ plots). We used $\alpha = 0.05$ to determine the significance of main effects and the interaction term for all analyses and, if site effects were significant, we made pairwise comparisons among sites using Tukey contrasts. We report unadjusted *P*-values for multiple tests because the power to detect any effects would be low with adjusted values, although we interpret results with caution (García 2004; Nakagawa 2004). To determine the relative dominance of the main two canopy-forming species (marri and jarrah) within plots, we divided the number of marri stems in each plot by the total number of eucalypt stems (marri and jarrah) and then calculated an average for each site. All analyses were performed in R version 3.0.2 (R Core Team 2013).

## Results

### *Patterns of feeding activity in unmined forest*

The most common non-proteaceous feed-tree species in unmined forest plots were jarrah (82–100% of plots), marri (28–100%) and sheoak (24–40%; Fig. 3). Jarrah was commonly eaten in unmined forest at AA (25%) and BBM (28.6%), but not NBG (0.9%). Marri was fed on in 65% of unmined forest plots at AA, 29.6% at NBG and 22.9% at BBM. Sheoak was fed on in 1% of plots at NBG and 10% at AA (Fig. 3).

Nine proteaceous food plants (*Hakea*, *Banksia* and *Persoonia* spp.) were recorded in unmined forest plots at both NBG and BBM, whereas five were recorded at AA (those indicated in Fig. 3, as well as *Hakea amplexicaulis*). At BBM, cockatoos fed on four proteaceous species in unmined forest, with *Banksia sessilis* being consumed in 25.7% of plots and *Hakea undulata* in 14.3% (Fig. 3). Cockatoos fed on four proteaceous species in unmined forest at NBG (*B. sessilis*, *B. squarrosa*, *H. prostrata* and *H. undulata*), each in less than 5% of plots, whereas only *Persoonia longifolia* residues were recorded in unmined forest plots at AA (Fig. 3).

### *Structure and floristics of revegetation*

Jarrah was present in a large proportion of revegetation plots at all three sites (63–98%) and marri was present in 35.4% of plots at BBM and ~90% of plots at both NBG and AA (Fig. 4). Sheoak was present in ~50% of BBM plots and 20% of AA plots (Fig. 4). Wandoo was present in ~50% of plots at BBM, and *P. longifolia* was present in one plot at AA (Fig. 4). Revegetation at NBG had a higher proportion of marri stems (mean ± s.e.: 0.58 ± 0.03) than did both BBM (0.31 ± 0.05) and AA (0.24 ± 0.02). There were at least 10 *Banksia* and *Hakea* species present in revegetated plots at NBG (those indicated in Fig. 4, as well as *Hakea cyclocarpa*, *H. incrassata* and *H. ruscifolia*), whereas there were at least six at both BBM and AA (Fig. 4).

*Banksia* stem density was higher in exterior than interior plots and decreased with plot age at NBG, whereas it increased with plot age at AA (Table 2, Fig. 5). *Banksia* stem density at AA was lower than at both BBM ($P = 0.049$) and NBG ($P = 0.001$). Jarrah stem density at AA was higher than at BBM ($P < 0.001$; Fig. 5). Marri stem density at NBG was higher than at both AA ($P < 0.001$) and BBM ($P < 0.001$), and decreased with plot age

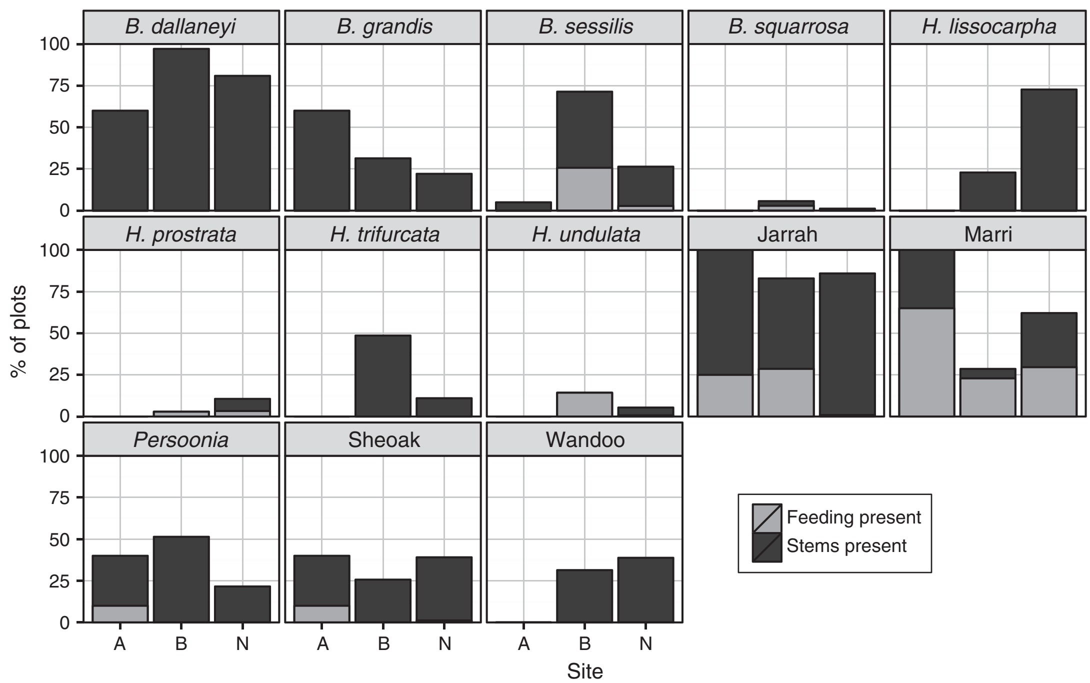


**Fig. 3.** Percentage of unmined forest plots at each site that contained cockatoo food plant species (*Banksia* and *Hakea* spp., jarrah, marri, *Persoonia longifolia*, sheoak, and wandoo) and cockatoo feeding residues from those species. A, Alcoa of Australia Ltd Huntly bauxite mine (AA); B, BHP Billiton Worsley Alumina Boddington Bauxite Mine (BBM); N, Newmont Boddington Gold mine (NBG).

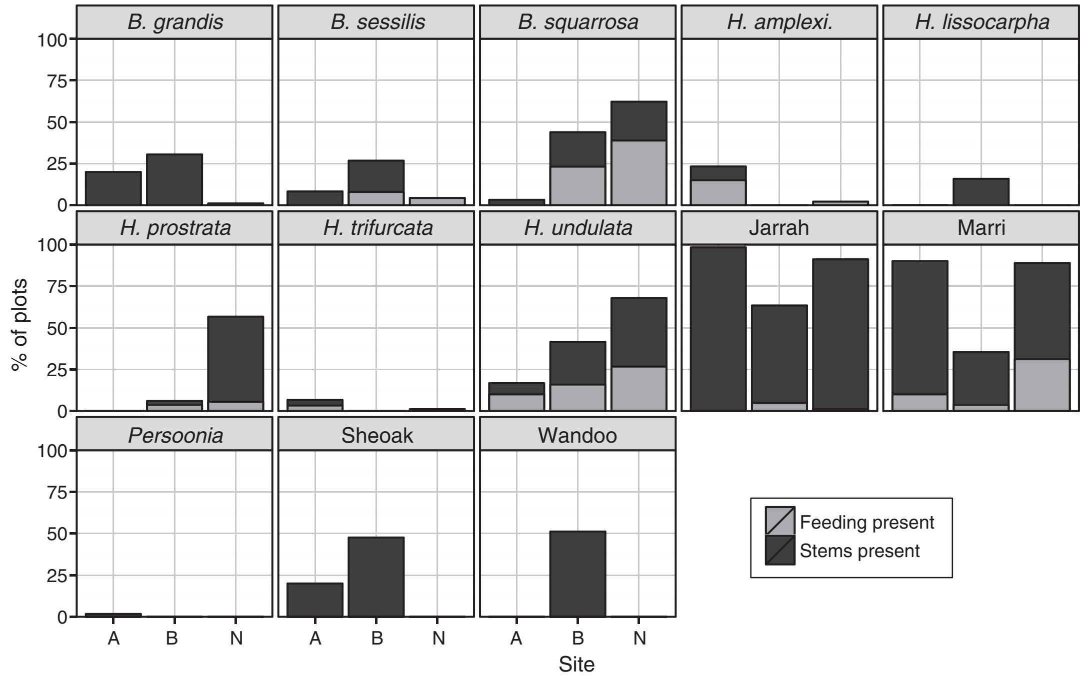


**Fig. 4.** Percentage of revegetation plots at each site that contained cockatoo food-plant species (*Banksia* and *Hakea* spp., jarrah, marri, *Persoonia longifolia*, sheoak and wandoo) and cockatoo feeding residues from those species. A, Alcoa of Australia Ltd Huntly bauxite mine (AA); B, BHP Billiton Worsley Alumina Boddington Bauxite Mine (BBM); N, Newmont Boddington Gold mine (NBG). The presence of stems of *Persoonia longifolia*, sheoak, wandoo, *Banksia grandis*, *B. sessilis*, *Hakea amplexicaulis*, *H. lissocarpha* and *H. trifurcata* was not systematically recorded for NBG plots, and the presence of *H. amplexicaulis* stems was not systematically recorded for BBM plots, although any feeding residues from those species were recorded if present.

at NBG, but not the other two sites (Table 2, Fig. 5). Species richness of potential food plants decreased with plot age at NBG and BBM and was higher at NBG than at BBM ($P < 0.001$), where it was, in turn, higher than at AA ($P = 0.028$). Canopy cover was higher in interior than exterior plots, increased with plot age at all three sites, and was higher at NBG than at AA ($P = 0.012$; Table 2, Fig. 5). Canopy height increased with plot age at AA and decreased slightly at NBG (Fig. 5). Canopy height at NBG was higher than that at BBM ($P < 0.001$) and lower than that at AA ($P < 0.001$). Understorey height and *Hakea* stem density did not vary with plot age, location or site (Table 2).

### *Patterns of feeding activity in revegetation*

One-third of revegetation plots at NBG contained feeding residues from marri, whereas only 10% of plots at AA and 3.7% of plots at BBM did (Fig. 4). Jarrah was eaten infrequently at all sites (<5% of plots; Fig. 4). Sheoak, wandoo and *P. longifolia* were not fed on in revegetation at any site; however, *P. longifolia* was largely absent from revegetated sites, occurring only in 1% of plots at AA (Fig. 4). Cockatoos fed on eight *Hakea* spp. in revegetation at NBG (those indicated in Fig. 4, as well as *Hakea cyclocarpa*, *H. incrassata* and *H. ruscifolia*), but only two and three species at BBM and AA respectively (Fig. 4). Three *Banksia* spp. were eaten in revegetation at NBG, two at BBM and none at AA (Fig. 4).

The likelihood of a plot containing feeding residues decreased with plot age at all three sites (Table 3, Fig. 6). Cockatoo feeding activity on *Banksia* spp. at NBG was higher than that both at AA ($P = 0.003$) and BBM ($P = 0.044$), whereas use of *Hakea* spp. at AA was higher than that at NBG ($P = 0.048$; Table 3, Fig. 7). The number of *Hakea* feeding residues decreased with plot age, whereas the number of *Banksia* residues did not show any relationship with plot age (Table 3, Fig. 7). There was no significant difference between interior and exterior plots for foraging on any species, and use of jarrah and marri did not differ according to plot age or site (Table 3, Fig. 7).

## Discussion

We surveyed a chronosequence of revegetation at three mine sites in the jarrah forest of south-western Australia to document successional changes in black cockatoo food-plant availability and utilisation. Cockatoos fed on revegetation at all three mine sites, despite variations in vegetation age, structure and floristics. Feeding on proteaceous and myrtaceous food plants occurred within 4 and 7 years of revegetation being established, respectively, indicating that some food resources are restored quickly after mining disturbance in the jarrah forest.

### *Successional changes in feeding activity*

We identified successional changes in cockatoo feeding activity in mine site revegetation aged between 4 and 23 years old. Feeding on proteaceous shrubs was greatest in younger revegetation and declined as revegetation age increased, probably because of the concurrent floristic changes we

**Table 2. General linear model results for the effects of plot age, site and location (interior or exterior) on vegetation structural and floristic variables**
Significant terms are indicated in bold

| Parameter | Location ($F_{1,225}$) | Age ($F_{1,225}$) | Site ($F_{2,225}$) | Age × site ($F_{2,225}$) |
|---|---|---|---|---|
| *Banksia* stem density[A] | | | | |
| *F*-value | **4.78** | **4.76** | **6.90** | **6.06** |
| *P*-value | **0.030** | **0.030** | **0.001** | **0.003** |
| *Hakea* stem density | | | | |
| *F*-value | 1.25 | 3.76 | 1.84 | 0.09 |
| *P*-value | 0.264 | 0.054 | 0.162 | 0.916 |
| Jarrah stem density | | | | |
| *F*-value | 1.03 | 1.09 | **17.39** | 1.59 |
| *P*-value | 0.312 | 0.297 | **<0.001** | 0.206 |
| Marri stem density | | | | |
| *F*-value | 0.05 | 0.52 | **34.02** | **20.64** |
| *P*-value | 0.832 | 0.473 | **<0.001** | **<0.001** |
| Species richness of potential food plants | | | | |
| *F*-value | 0.03 | 3.27 | **23.75** | **13.55** |
| *P*-value | 0.871 | 0.07 | **<0.001** | **<0.001** |
| Canopy cover | | | | |
| *F*-value | **6.60** | **31.67** | **4.35** | **6.49** |
| *P*-value | **0.011** | **<0.001** | **0.014** | **0.002** |
| Canopy height | | | | |
| *F*-value | 0.33 | **125.86** | **13.52** | **39.38** |
| *P*-value | 0.568 | **<0.001** | **<0.001** | **<0.001** |
| Understorey height | | | | |
| *F*-value | 0.26 | 0.32 | 0.23 | 2.66 |
| *P*-value | 0.609 | 0.572 | 0.798 | 0.072 |

[A]Degrees of freedom for the tests of *Banksia* stem density were as follows: location ($F_{1,158}$), age ($F_{1,226}$), site ($F_{2,226}$), age × site ($F_{2,226}$).

recorded in revegetation plots. Younger plots were characterised by a thick proteaceous understorey that became much sparser and was replaced by a closed canopy of marri and jarrah in older plots.

The increased dominance of eucalypts in older revegetation was not reflected in increased utilisation. These species were frequently eaten in unmined forest, although there was some variation among mine sites. Jarrah was rarely eaten in revegetation across all sites or in unmined forest at NBG, but was frequently used in unmined forest at AA and BBM. Because jarrah stems were common in both revegetation and unmined forest at all three mine sites, this implies that jarrah was generally eaten less frequently in revegetation than unmined forest, despite its availability (particularly at AA and BBM).

Marri also seemed to be consumed less frequently in revegetation than in unmined forest, although, again, there was some variability among mine sites. Marri feeding was common in unmined forest at all three sites, especially at BBM. Although a lower proportion of unmined forest plots at BBM contained marri, it was eaten almost as frequently as at NBG (30% of all plots; BBM: 23%), implying that, even when marri is scarce, black cockatoos preferentially feed on marri. In revegetation, the heaviest marri feeding occurred in intermediate-aged plots (mostly at NBG), with feeding in some older plots at AA and in one at BBM. Even accounting for this variation among mine sites, the overall pattern is that jarrah and marri are eaten less frequently in revegetation than in unmined forest.

Several factors could account for these differences in eucalypt feeding activity between revegetation and unmined forest. First, the frequency of flowering and, consequently, fruiting events may differ between revegetation and unmined forest. Cockatoos opportunistically feed on marri and jarrah trees that have large fruit crops following prolific flowering events (Johnstone *et al*. 2013*b*). Marri fruit availability can vary significantly from year to year because the trees may flower heavily only every 3–4 years and the seeds are released 2–2.5 years after flowering (Seddon 1972; Powell 1990), suggesting that periods of low fruit availability are likely to occur. Thus, at a landscape scale, cockatoos shift between feeding on marri and jarrah according to what is fruiting (Johnstone *et al*. 2013*b*), which may account for the higher feeding activity on jarrah observed in unmined forest in an earlier study at NBG (Biggs *et al*. 2011). Second, young trees in revegetated areas are unlikely to provide the large fruit crops that older trees in unmined forest can. Additionally, high tree stem densities – typically much higher in revegetation than in unmined forest – can limit tree growth rates (Stoneman *et al*. 1997; Grigg and Grant 2009) and may also constrain flowering and fruit crops (Arista 1996; Williams *et al*. 2006). Glossy black cockatoos (*Calyptorhynchus lathami*) preferentially feed in trees with large fruit crops, probably because it is more energy efficient (Chapman and Paton 2005); so, the same may hold true for our study species in the jarrah forest. Cooper *et al*. (2003) found that marri trees fed on by the red-tailed black cockatoo in unmined forest had a higher fruit seed number than did non-feed trees, although that study did not assess the total fruit load of trees. Finally, there may be differences in fruit quality, as well as overall fruit quantity, between revegetation and unmined forest that may explain why marri and jarrah were eaten less frequently in revegetation than in unmined forest, and this requires further investigation. Although the larger plot size used in unmined forest could account for the higher frequencies of feeding recorded there, this is likely to have been offset by lower food-plant densities in unmined forest; we, therefore, have confidence that our results accurately reflect patterns of cockatoo feeding activity.

The overall higher frequency of feeding in younger revegetation may also be related to vegetation structure. The more open structure of younger revegetation may provide cockatoos with improved access to food plants, whereas high tree stem densities and closed canopies in older revegetation could reduce accessibility for these large birds. Carnaby's and Baudin's cockatoos readily feed close to the ground (Saunders 1974*b*; Johnstone and Kirkby 2008), and so, the lack of a dense canopy in younger revegetation may facilitate their access to proteaceous shrubs and young eucalypts in these areas. The higher abundance and availability of proteaceous foods that we recorded in younger revegetation may be due to less competition for light and water than in older, denser revegetation.

### *Management implications*

Revegetated mine pits in the jarrah forest provide food for black cockatoos within 4 years and continue to do so until at least 23 years after revegetation, which broadens the period of use

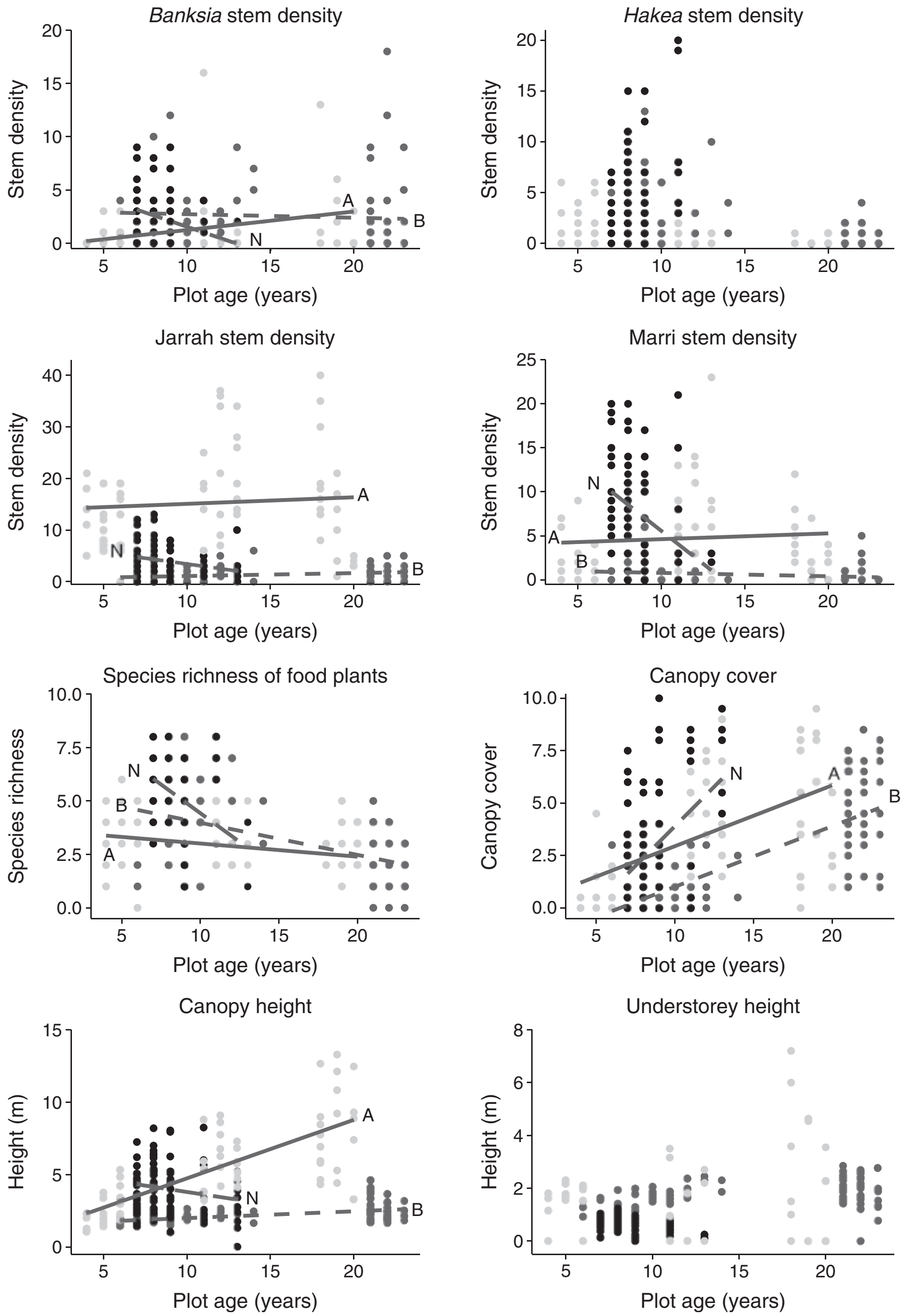


**Fig. 5.** Scatterplots of structural and floristic variables against plot age. Fitted lines are shown for variables that had a significant relationship with plot age or site: Alcoa of Australia Ltd Huntly bauxite mine (AA) (A, light grey dots, solid line), BHP Billiton Worsley Alumina Boddington Bauxite Mine (BBM) (B, dark grey dots, short dashed line) and Newmont Boddington Gold mine (NBG) (N, black dots, long dashed line). An outlier (31 stems, 20 years old) was excluded from the *Banksia* stem-density plot to aid graphical interpretation. However, the fitted line corresponds to the full dataset.

documented by Lee *et al*. (2010, 2013*b*). We did not measure revegetation younger than 4 years; however, because the mining and revegetation process takes 2–3 years for bauxite mines in the jarrah forest (Koch 2007), we know that these areas do not provide food resources for at least that time and, hence, potentially up to 7 years after initial forest clearing if birds do not feed on revegetation younger than 4 years. Some mining landscapes, such as the larger open-cut mining area at NBG, may never sustain food resources or may only do so over longer periods of time. Nonetheless, feeding did occur in smaller revegetated satellite pits at NBG, indicating that food plants can be returned to a range of mined landscapes if appropriate revegetation prescriptions are applied (Lee *et al*. 2013*b*).

Marri and jarrah fruits are important foods for BBC and FRTBC (Johnstone and Kirkby 1999, 2008); so, the ability of mine-site revegetation to provide these fruits is likely to be important to cockatoo conservation in production landscapes. Past forestry practices in unmined forest have increased the proportion of jarrah to marri (Abbott and Loneragan 1986) and, more recently, these two species have experienced decline and die-off caused by disease, drought and extreme heat (Paap

**Table 3. General linear model results for the effects of plot age, site and location (interior or exterior) on the presence of cockatoo feeding residues in a plot and the number of feeding residues from *Banksia* spp., *Hakea* spp., jarrah and marri**

Significant terms are indicated in bold

| Parameter | Location ($F_{1,225}$) | Age ($F_{1,225}$) | Site ($F_{2,225}$) | Age × site ($F_{2,225}$) |
|---|---|---|---|---|
| Feeding present or absent | | | | |
| *F*-value | 1.82 | **4.72** | 0.84 | 0.24 |
| *P*-value | 0.178 | **0.031** | 0.435 | 0.788 |
| *Banksia* spp. residues | | | | |
| *F*-value | 3.59 | 0.00 | **5.64** | 1.93 |
| *P*-value | 0.059 | 0.999 | **0.004** | 0.147 |
| *Hakea* spp. residues | | | | |
| *F*-value | 0.02 | **15.68** | **3.38** | 2.22 |
| *P*-value | 0.885 | **<0.001** | **0.036** | 0.111 |
| Jarrah residues | | | | |
| *F*-value | 2.54 | 0.00 | 0.17 | 0.62 |
| *P*-value | 0.113 | 0.999 | 0.845 | 0.537 |
| Marri residues | | | | |
| *F*-value | 2.90 | 0.23 | 1.64 | 0.69 |
| *P*-value | 0.090 | 0.631 | 0.197 | 0.501 |


**Fig. 6.** Fitted logistic regression model to predict likelihood of detecting black cockatoo feeding residues in revegetation plots on the basis of age and site: Alcoa of Australia Ltd Huntly bauxite mine (AA) (A, light grey dots, long dashed line), BHP Billiton Worsley Alumina Boddington Bauxite Mine (BBM) (B, dark grey dots, short dashed line) and Newmont Boddington Gold mine (NBG) (N, black dots, solid line). 0, feeding residues absent from a plot; 1, feeding residues present in a plot. The horizontal lines represent the proportion of unmined forest plots at each site that contained feeding residues: A, AA (80%); B, BBM (74%); N, NBG (37.4%).

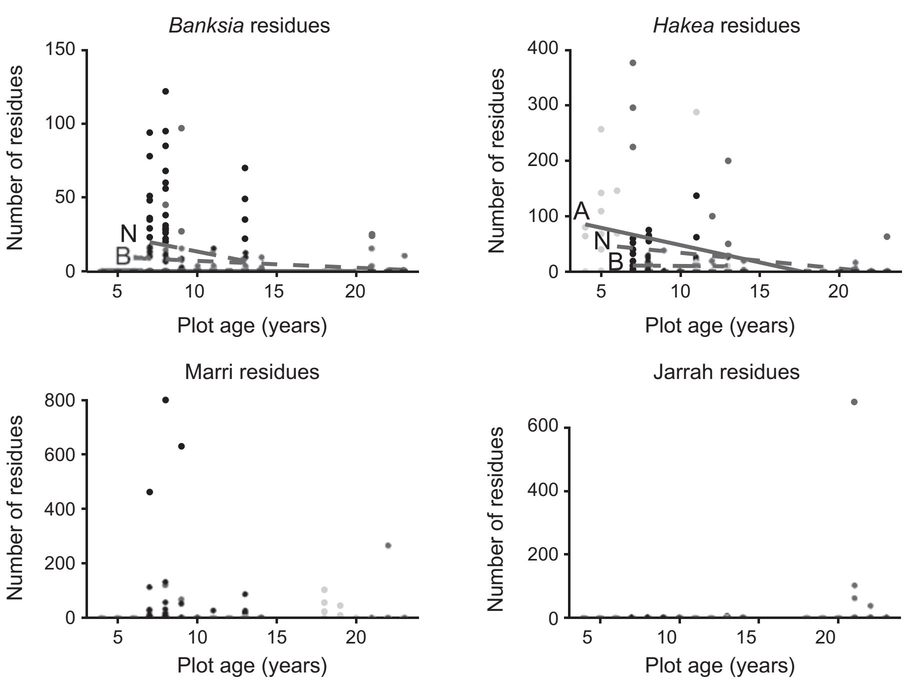


**Fig. 7.** Scatterplots of number of feeding residues against plot age. Fitted lines are shown for variables that had a significant relationship with plot age or site: Alcoa of Australia Ltd Huntly bauxite mine (AA) (A, light grey dots, solid line), BHP Billiton Worsley Alumina Boddington Bauxite Mine (BBM) (B, dark grey dots, short dashed line) and Newmont Boddington Gold mine (NBG) (N, black dots, long dashed line). One outlier (815 residues, 6 years old) was excluded from the *Hakea* residue plot to aid graphical interpretation. However, the fitted lines correspond to the full dataset.

*et al*. 2008; Matusick *et al*. 2013). The value of revegetation as feeding habitat for black cockatoos will need to be balanced against potentially competing land uses in the jarrah forest. For example, timber production may demand more jarrah and less marri, whereas water catchment will likely demand reduced stems densities of both species. Thus, while acknowledging that land managers will need to balance these competing demands, our study clearly showed that it is important that revegetated areas contain an appropriate proportion and number of marri and, to a lesser extent, jarrah stems, so as to provide appropriate feeding habitat for black cockatoos. Almost 25% of eucalypt stems at AA were marri, being slightly higher than the 4 : 1 ratio of jarrah to marri generally found in unmined forest and used in Alcoa's seed mix (Grant and Koch 2007; Koch and Samsa 2007). Although revegetation prescriptions were not available for the other two mines, revegetation at BBM, and NBG in particular, contained even higher proportions of marri stems relative to jarrah. Longer persistence of a proteaceous understorey may be aided by lower eucalypt stem densities, which has been proposed as a climate-change adaptation strategy for the forest (Wardell-Johnson *et al*. 2015), although mine-completion criteria for the establishment of certain numbers of potential sawlogs (Grant 2006) would need to be revised if such an approach were adopted. Regardless, revegetation practices are likely to play an important role in the future provision of cockatoo food resources in revegetated areas of jarrah forest.

Further research is needed to determine whether feeding rates in revegetated areas increase beyond 23 years post-revegetation and become similar to feeding rates in unmined forest. Although we have demonstrated feeding by black cockatoos in revegetation up to 23 years of age, we have not established equivalence of the food resources provided by revegetated pits with surrounding mature forest. Additionally, without data on energy and nutrient quality of available food crops, or the proportion actually consumed by cockatoos, we cannot tell whether revegetated pits were used to capacity or whether there was an excess of uneaten food, nor can we establish the energetic equivalency or otherwise of revegetation and unmined forest.

The shift in feeding habits as revegetation ages may reflect differences in other resources provided by older revegetation. Lee *et al*. (2013*a*, 2013*b*) observed that black cockatoos used revegetation for feeding, but not roosting, perhaps because of the small size and open canopy of overstorey trees in intermediate-aged revegetation. Cockatoos prefer to roost in taller trees with wider canopies (Johnstone and Kirkby 2008). Whereas the larger trees in older revegetation may provide suitable roosts, cockatoos have not been observed using these areas for roosting (T. Doherty, pers. obs.). Additionally, since suitably sized nesting hollows for black cockatoos generally occur in trees aged 130–200+ years old (Whitford and Williams 2002; Johnstone *et al*. 2013*a*), the trees at our sites have not yet developed suitable nesting hollows.

By sampling across a range of revegetation ages, we have shown that cockatoos feed in revegetation that is both younger and older than that sampled in previous studies (Lee *et al*. 2010, 2013*b*), which further supports the important role that revegetation plays in promoting the persistence of fauna in production landscapes. Documented successional changes in feeding activity confirm that the temporal scale of monitoring can influence our understanding of faunal responses to revegetation. A key issue in gaining such information is the length of time over which successional processes influence resource availability, compared with the shorter time periods over which fauna responses have typically been monitored (Haslem *et al*. 2011). Consequently, monitoring of fauna recolonisation should be conducted over appropriate temporal scales, for example, by using chronosequences (Craig *et al*. 2012) or longitudinal studies (Davis and Doherty 2015), to better understand how successional processes in revegetation influence fauna population persistence in production landscapes.

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