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Feeding activity of threatened black cockatoos in mine-site rehabilitation in the jarrah forest of south-western Australia

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Abstract. Land clearing threatens three black cockatoo species (forest red-tailed black cockatoo, (*Calyptorhynchus banksii naso*), Carnaby's cockatoo (*Calyptorhynchus latirostris*), and Baudin's cockatoo (*Calyptorhynchus baudinii*) endemic to south-western Australia, so revegetation is important to their recovery. Over three years we studied cockatoo activity in 7–14-year-old mine-site rehabilitation in the region's jarrah (*Eucalyptus marginata*)–marri (*Corymbia calophylla*) forest to give the most detailed description to date of the use of rehabilitation by the birds. Pits varied floristically and structurally (despite similar rehabilitation prescriptions), but interior and exterior plots (100 m^2) were similar within pits. Using feeding traces (e.g. chewed husks), and behavioural observations we confirmed feeding within eight years of revegetation. Plots containing feeding trace were similar to plots without, so factors determining black cockatoo feeding may not be apparent at small scales. Returning food resources reflected vegetation succession, with regenerating marri and fast-maturing proteaceous species providing most food. Carnaby's cockatoo ate *Banksia* and *Hakea* seeds and Baudin's cockatoo and the forest red-tailed black cockatoo consumed marri seeds. *Banksia squarrosa*, *Hakea undulata*, *H. prostrata* and marri were common foods in all years. Revegetation efforts elsewhere should consider these species, within the constraints of rehabilitation protocols addressing multiple aims.

Additional keywords: feeding traces, revegetation.

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Introduction

Re-establishing native vegetation returns habitat resources to anthropogenically disturbed landscapes, facilitating faunal recolonisation (Munro *et al*. 2007; Nichols and Grant 2007). Resources may return over decades, emphasising the need to document when fauna return and their use of revegetation (Gould 2011). We describe feeding by three threatened black cockatoo species within young (<15 years after establishment) mine-site rehabilitation in the jarrah (*Eucalyptus marginata*)–marri (*Corymbia calophylla*) forest of south-western Australia.

The forest red-tailed black cockatoo (*Calyptorhynchus banksii naso*) (FRTBC) (a subspecies), Carnaby's cockatoo (*Calyptorhynchus latirostris*), and Baudin's cockatoo (*Calyptorhynchus baudinii*) are endemic to south-western Australia. They are listed as threatened under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* and as Schedule 1 fauna ('rare or likely to become extinct and in need of special protection') under Western Australia's *Wildlife Conservation Act 1950*. Carnaby's cockatoo and Baudin's cockatoo are endangered under the IUCN Red List of Threatened Species (Birdlife International 2012*a*, 2012*b*).

Baudin's cockatoo feeds intensively on marri, but also eats seeds, buds, and flowers of proteaceous shrubs and myrtaceous trees, insect larvae, orchard fruit, and other plants (Johnstone and Storr 1998; Johnstone and Kirkby 2008; Lee *et al*. 2013). Seeds from jarrah and marri comprise most of the FRTBC diet, but the FRTBC also consumes seeds from other eucalypts, forest sheoak (*Allocasuarina fraseriana*), and snottygobble (*Persoonia longifolia*) (Johnstone and Storr 1998; Johnstone and Kirkby 1999; Cooper *et al*. 2003). Carnaby's cockatoo consumes seeds, flowers, and nectar of jarrah, marri, *Banksia* spp., *Hakea* spp., and *Pinus* spp. (Saunders 1974*a*, 1974*b*, 1980; Lee *et al*. 2013) and insects (Saunders 1980).

Habitat loss is a key threatening process for all three black cockatoos (Chapman 2008; Garnett *et al*. 2011; Department of Environment and Conservation 2012; Johnstone *et al.* 2013*a*, 2013*b*). The jarrah–marri forest, the largest contiguous forest in south-western Australia, supports timber and mineral production that require land clearing, albeit temporarily. Water catchment areas in the forest are thinned to improve water accession (Conservation Commission of Western Australia 2004). Despite broad agreement that land uses in the forest should maintain or restore fauna habitat (Koch and Hobbs 2007), there is little published information on whether revegetation is effective for black cockatoos (Weerheim 2008; Lee *et al*. 2010, 2013).

Documenting when black cockatoos feed in revegetated areas is difficult, because observation is unsuited to detecting low-density, mobile species that often occupy sites briefly. Therefore, black cockatoos are detected infrequently during observational surveys (Craig and Roberts 2005; Nichols and Grant 2007; Weerheim 2008). However, feeding black cockatoos leave distinctive residues, including chewed fruit husks, flowers, flower spikes, and buds; opened seed pods, and broken branches cut at a distinctive 45° angle (Saunders 1974*a*, 1974*b*; Johnstone and Kirkby 1999; Cooper 2000; Cooper *et al*. 2003; Weerheim 2008; Biggs *et al*. 2011). They leave unique feeding patterns on marri fruit husks (Saunders 1974*b*; Cooper 2000; Cooper *et al*. 2003; Western Australian Museum 2013). Feeding residues can also be quantified, as applied for other taxa (e.g. Stuart and Stuart 2000). Lee *et al*. (2010) demonstrated that feeding residues complemented behavioural observations in assessing black cockatoo activity at rehabilitated mine sites in the jarrah–marri forest, but did not assess vegetation-rehabilitated sites in detail in relation to feeding.

This paper extends previous work through detailed descriptions of feeding by black cockatoos within young (7–14-year-old) mine-site rehabilitation at the Newmont Boddington Gold mine (hereafter NBG) in the jarrah–marri forest. We aimed to document: (1) structural and floristic variation in vegetation across the pits; (2) differences in feeding activity by the three black cockatoos based on feeding residues; (3) any 'edge' effect reflecting preferential use of vegetation at the interior or exterior of pits; (4) changes in feeding activity over time by comparing feeding residue deposition in successive samples; and (5) structure and floristics associated with feeding. We also used observational methods to gather additional information on species occurrence and behaviour. We comment on the implications of findings for mine-site rehabilitation in the jarrah forest and for broader habitat-restoration efforts.

Methods

Study area

The NBG mine is a large, open-cut gold and copper mine along the eastern margin of the jarrah–marri forest at the ecotone to the wandoo (*Eucalyptus wandoo*) woodland of the Avon Wheatbelt bioregion (Rayner *et al*. 1996) (for maps see Lee *et al*. 2013). Mean annual rainfall is 700–800 mm. At the time of the study, there were 50 rehabilitated mine pits at NBG totalling ~190 ha.

Ecology of black cockatoos at NBG

Lee *et al*. (2013) studied site occupancy, habitat use, and feeding by black cockatoos at NBG during 2008–10. FRTBC showed similar group sizes and occupancy across seasons, indicating year-round residency and no seasonal movements or grouping patterns. Carnaby's cockatoos were most abundant in spring and summer, suggesting the periodic presence of migrating or transient flocks as well as year-round residents. Baudin's cockatoos were scarce during summer (their peak breeding period); their presence at NBG likely reflects seasonal migration of non-breeding flocks into jarrah–marri forest (~April to October) (Johnstone and Kirkby 2008). Sixteen native food plant species were documented; Carnaby's cockatoos feed on at least ten.

All three cockatoos were observed in modified or human-made habitats at NBG and its surrounds, including native forest, mine-site rehabilitation, remnant vegetation in paddocks, and pine plantations. All species were encountered mainly in native forest. Carnaby's cockatoos and Baudin's cockatoos were encountered next most frequently in mine-site rehabilitation areas, whereas FRTBC were not sighted in rehabilitation areas.

Rehabilitated mining pits

The former mining pits sampled were smaller 'satellite' pits outside the main mining area, which consists of two deep (>500 m) and extensive (>1 km in diameter) pits (Rayner *et al*. 1996). Pits were rehabilitated following prescriptions in Environmental Protection Authority (1994) and Rayner *et al*. (1996), which resemble those used for other mines within the jarrah–marri forest in landscaping, soil management, seeding, and planting (Koch and Samsa 2007). Landscaping of pits restored natural topographic profiles, so the elevation of pit areas was similar to that of the surrounding landscape. Native forest bordered all pits and no location in any pit was more than a few hundred metres from native forest.

While some pits were rehabilitated as early as 1992, most were rehabilitated between 2000 and 2002. Prescriptions relied on the natural seed bank in soils used for rehabilitating pits, direct (broadcast) seeding and nursery-reared seedlings. Seed mixes contained only species endemic to native forest at the site, including *E. marginata*, *C. calophylla*, and *E. wandoo* as canopy-forming species and *Banksia* spp., *Hakea* spp., and *Allocasuarina* spp. as mid-storey and shrub species. Rates and methodology of seeding and fertiliser application were standardised across pits.

Nine rehabilitated mining pits were surveyed using plot-based sampling to obtain floristic and structural vegetation data and describe spatial, temporal, and species patterns in feeding residues (Fig. 1). Chosen pits had similar topographies and size. All pits were within a 4-km radius. Pits less than 1 ha, inaccessible to vehicles, and <1 km to mining were excluded. All nine sites lay within 1–2 km of a water source and had contiguous native forest within 20 m of at least one side. Vegetation was re-established in: 1996 ($n = 1$ pit), 1998 ($n = 1$), 2000 ($n = 2$), 2001 ($n = 3$), and 2002 ($n = 2$). Eight pits were established with similar seed mixes, having jarrah and marri as the myrtaceous species, plus proteaceous species. The pit 'WTR' differed, being dominated by *E. wandoo*.

Structure and floristics of pit vegetation

We sampled vegetation structure and floristics within the nine pits to compare pits and sites within pits where black cockatoos did or did not feed. We sampled 10 replicate plots (each 100 m^2 in area) within pits, providing $n = 90$ plots (total area = 9000 m^2). Each pit contained five interior plots (>25 m from any edge), located at equal intervals along a transect running diagonally across the entire pit. Each pit contained five exterior plots, positioned equidistantly around the perimeter (Fig. 2).

Plot dimensions were 10 m × 10 m for interior plots and 20 m × 5 m for exterior plots. All plots were separated by at least 50 m. The longer (20 m) edge of the exterior plot was positioned at the outer edge of the vegetation at each site (so plots measured only 5 m inwards from outermost stems). We used interior

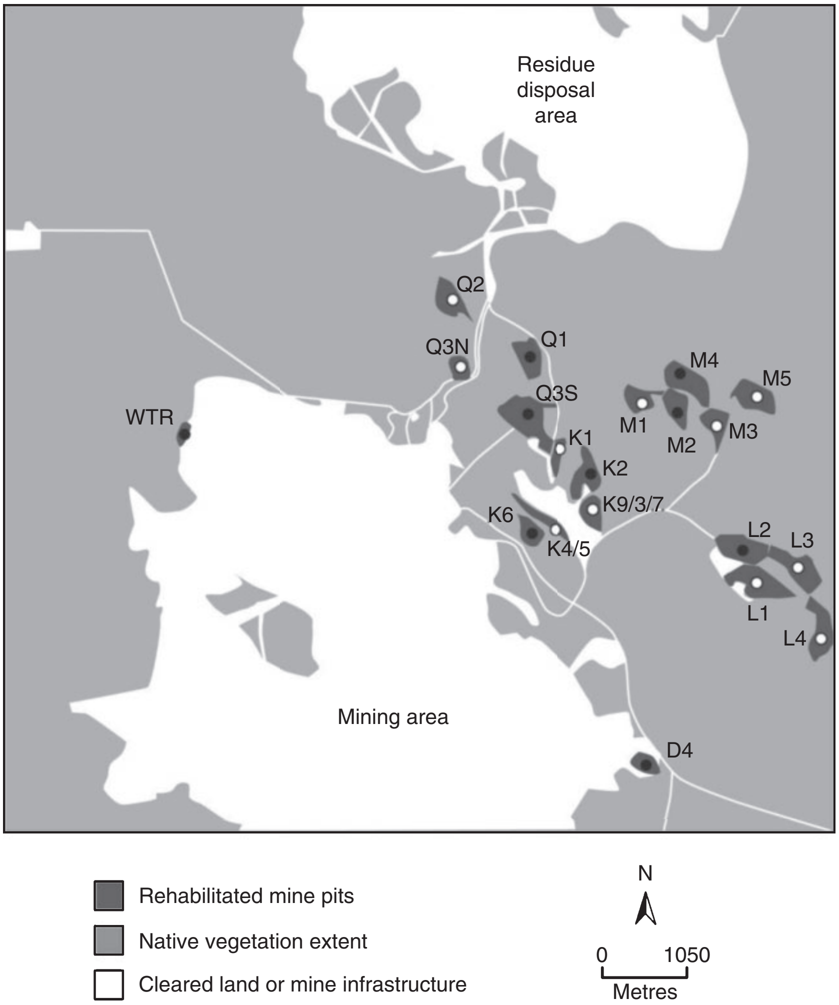

Fig. 1. General site map and location of pits. Black dots indicate pits used in the vegetation sampling.

and exterior plots to examine potential edge effects related to vegetation structure or feeding.

Table 1 describes the sampling procedure for each variable. Measurements of canopy cover were taken using a 10-m point-intercept transect situated within each sampling plot. For the 10 m × 10 m interior plots, we positioned the transect through the middle of the plot along the same axis as the transect running across the entire pit (Fig. 2). For the 20 m × 5 m exterior plots, we positioned the transect parallel to the long axis of the plot and in the middle of the plot, so that the transect was 2.5 m from the long (20 m) side of the plot and 5 m from short (5 m) side of the plot (Fig. 2).

Measurements of other variables were taken using each plot as a 100-m^2 sampling area. For measurements of canopy height, non-canopy height and stem density, an individual plant was considered a ‘stem’ if it was at least 0.5 m high. Smaller stems were not measured. A stem was within a plot if at least 50% of its bole was within plot boundaries.

We used structural and floristic variables to compare vegetation between pits and between interior and exterior plots (Table 1). When comparing plots where feeding did or did not occur we used variables that potentially influence feeding by black cockatoos (Johnstone and Kirkby 1999; Biggs *et al*. 2011; Johnstone *et al*. 2013*b*) (Table 1).

Feeding residues in rehabilitated mine pits

We used feeding residues to investigate patterns in feeding activity within and across pits, including between interior and exterior vegetation. Residues were collected in the plots established for sampling vegetation structure and floristics. Given the close proximity of the pits to contiguous native forest, factors that influence where birds feed within pits should largely reflect the pit vegetation rather than other factors (e.g. distance to cover).

We searched plots for feeding residues by examining the ground beneath potential food plants (0.5 m high or taller). Residues within the area covered by the canopy were included, even if the canopy extended beyond plot boundaries, but residues belonging to a food plant whose stem was outside the plot were excluded. If canopies of two or more conspecific plants overlapped, we allocated feeding residues equally. If the canopy of a plant in the plot overlapped the canopy of a plant outside, we

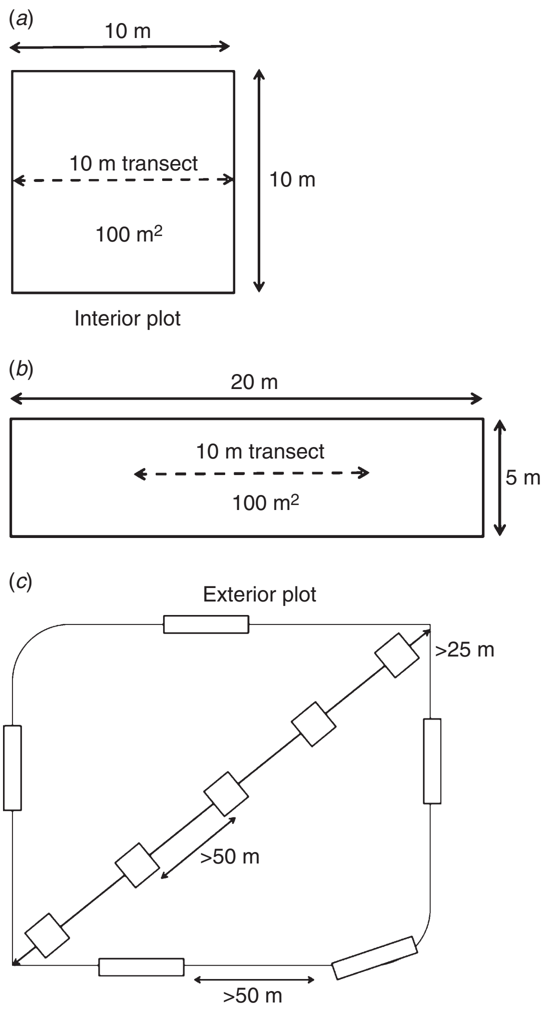

Fig. 2. Dimensions and layout of the feed residue and vegetation sampling design: (*a*) 10 m × 10 m interior plot and (*b*) 20 m × 5 m exterior plot (>25 m from the edge of the pit), and (*c*) positions of sampling plots around the rehabilitation for sampling (not drawn to scale).

also allocated feeding residues equally. We removed litter to identify feeding residues covered by leaf fall.

Feeding residues were: (a) chewed myrtaceous fruit husk (marri, jarrah); (b) cut proteaceous branch (*Banksia* and *Hakea* spp.); and (c) cracked proteaceous seed pod (*Hakea* spp.). Lee *et al*. (2013) presented an inventory of the types of feeding residues observed at NBG; they observed black cockatoos feeding on 10 of the 16 documented native food plants at NBG and described the types of feeding residue. Our personal observations indicate that the longevity of feeding residues varies between plant species and residue types. Marri husks and cut branches are often identifiable for years. Jarrah husks are smaller, degrade more quickly, and may be difficult to identify after 1–2 years. Seed pods persist only for weeks to months, depending on plant species and substrate. We do not know if the different black cockatoos produce residues at similar rates.

Markings left on marri fruit husks by black cockatoos are well documented elsewhere, and can generally be attributed to species (Cooper 2000; Cooper *et al*. 2003 and included references). FRTBC leave a distinctive 45° angle slice. Baudin's cockatoos pry seeds out, leaving distinctive markings where the lower mandible pressed into the base of the husk. Carnaby's cockatoos chew through the side of the husk or use a modification of the technique used by Baudin's cockatoo (with the lower mandible impressions higher up on the fruit) (H. Finn, personal observation). Other birds that feed on marri leave different markings (Western Australian Museum 2013). Behavioural observations indicate that Carnaby's cockatoos rarely feed on marri fruits at NBG (Lee *et al*. 2013). Therefore we attributed all marri feeding residues to Baudin's cockatoos or FRTBC, although some may have come from Carnaby's cockatoos.

Black cockatoos are the only birds that feed on jarrah fruits, and they crack husks to extract seeds. However, fruits are too small to reliably attribute husks to any black cockatoo species. Feeding Carnaby's cockatoos cut branches of proteaceous shrubs, leaving a distinctive 45° angle slice (H. Finn, personal observation). We are unaware of any other species (or natural mechanism) that causes this damage. Finally, black cockatoos crack seed pods of some proteaceous shrubs when feeding.

Fruit husks were counted within the canopy diameter of each stem and summed for each 100-m^2 plot. In two plots husks were too abundant to count, so the total was estimated on the basis of the depth and area covered. Feeding residues for proteaceous plants were mainly broken branches and seed pods within the canopy diameter, or occasionally buds and flowers. Each residue type was counted for each stem of each food plant and summed for each 100-m^2 plot.

Plots were checked for feeding residues twice in winter (July 2009 and July 2010) and once in summer (January 2010). We manually removed feeding residues at the end of the first and second sampling sessions, so the residues observed during the second and third sampling sessions included only those feeding residues produced within six months before the sample. Residues on the first occasion likely accumulated over longer periods. For marri trees in two plots, the depth and extent of feeding residues precluded complete removal. We took photographs and used them on later samples to ensure that we recorded only recent feeding residues.

Comparisons of feeding and non-feeding plots

Tests for vegetation differences between plots where feeding did or did not occur were restricted to the first sampling occasion, because only phenological variables (flowering, seeding) might change significantly over the short intervals between sampling sessions or over the study. The study therefore represents a 'snapshot' of vegetation structure and floristics at one successional stage, not a longitudinal assessment.

Observations of black cockatoos

We conducted observational monitoring at 23 of the 50 rehabilitated mine pits at NBG over 25 months (Fig. 1). We aimed to assess whether the three species occurred in similar frequencies in the landscape around rehabilitated mine pits. Although Lee *et al*. (2013) reported on habitat use and group sizes of black cockatoos at NBG (including rehabilitation sites), that study used total sightings for each species across all habitat types from several sampling approaches.

Table 1. Structural, floristic and phenological variables measured on each plot

Variable	Definition
Structural variables	
Canopy cover[A]	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 a single canopy cover value between 0 and 10 for the plot.
Canopy height[A]	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.
Non-canopy height[A]	Mean height of plants from genera other than those regarded as canopy-forming (≥0.5 m height).
Vegetation density: living and dead levy pole touches at 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m and 3.5 m[B]	Measured at 1-m intervals along point-intercept transect using a levy pole graduated into 0.5-m gradations to a height of 3.5 m. We recorded whether any plant species, living or dead, was in contact with the levy pole at each 0.5-m gradation (not touching = 0; touching = 1). The 10 measurements for each height point were summed to give a single value between 0 and 10 for that height for the plot.
Total stem count for living and dead stems[A]	The total number of living and dead stems of any species (≥0.5 m height) in the plot. If a plant was multistemmed (e.g. coppice regrowth), we recorded this as one stem only. Any plant that was mostly or fully brown or grey, including leaves, was classified as dead.
Floristic variables	
Stem density of all food plants[A]	The number of stems of living plants (≥0.5 m height) within a plot for any of the 15 plant species known to be potential foods.
Stem density of major feed plant species[B]	The number of stems of living jarrah, marri, *H. undulata*, *H. prostrata* and *B. squarrosa* (≥0.5 m height) within a plot.
Individual plant structural variables	
Canopy width[B]	For every stem in the plot (both canopy and non-canopy species), we estimated the width of the canopy by holding the levy pole horizontally at the greatest width of the canopy. These values were averaged for each species to give a mean canopy-width for each species in the plot. Recorded for jarrah, marri, *H. undulata*, *H. prostrata* and *B. squarrosa*.
Height of five most abundant food plant species[B]	Mean height of stems (≥0.5 m height) of jarrah, marri, *H. undulata*, *H. prostrata* and *B. squarrosa*. If the tree was multistemmed, height was taken for the tallest stem.
Individual plant floristic variables	
Flowering or post-flowering[B]	If buds were present or had opened as flowers or if fallen flowers were present beneath the plant. Recorded for jarrah, marri, *H. undulata*, *H. prostrata* and *B. squarrosa*.
Seeding[B]	Open or closed seed pods were present. Recorded for jarrah, marri, *H. undulata*, *H. prostrata* and *B. squarrosa*.

[A] Variable used to compare different rehabilitation pits.
[B] Variable used to compare plots where feeding occurred with plots where no feeding occurred.

Monitored pits varied from 6 to 12 years old at the start of the monitoring (October 2008), with vegetation re-established in: 1996 ($n = 1$ pit), 1998 ($n = 1$), 1999/2001 ($n = 1$), 2000 ($n = 8$), 2001 ($n = 7$), and 2002 ($n = 6$). All monitored pits were: >1 ha in area, >1 km from active mining, within 1–2 km of a water source, and bordered (within 20 m) by contiguous native forest along at least one side.

We surveyed the 23 pits fortnightly in October–November 2008 and monthly from December 2008 to July 2010. During surveys, we occupied a vantage point near each pit within 4 h of dawn or dusk, observing the pit and its immediate surrounds for 5 min. These times coincided with peak feeding activity.

We recorded a species as present at a monitoring site if birds were detected: (1) visually, either within pit vegetation or flying directly above it, or (2) acoustically, based on contact calls originating within the pit or in native forest immediately adjacent (i.e. within 20 m of forest edge). Detections (visually or aurally) were recorded to species: the contact calls of FRTBC are distinctive and the similar contact calls of Carnaby's cockatoo and Baudin's cockatoo are discernible. Monitoring detections therefore indicated how frequently the species occurred in the immediate vicinity of the pit vegetation (rather than in direct contact with it).

We also conducted behavioural observations whenever birds were observed in contact with pit vegetation, either during low-level monitoring surveys or opportunistically during other research activities. Data were collected for the first 10 min of a sighting using scan sampling, and opportunistically thereafter (Altmann 1974). We attempted to observe all individuals present and record the flock's predominant activity (that of ≥50% of individuals during the 10-min scan), as well as flock size and any foods eaten.

Flock activity was classified according to predetermined activity states, including Roost-Rest (long-term roosting: >1 h); Roost-Short (short-duration roosting, e.g. brief roosting periods during feeding/foraging bouts or during pauses in flight); Fly (in flight); and Feed (consuming or processing foods, or actively searching for food). Roost-Short included birds roosting for short periods while travelling (e.g. between roost sites and feeding areas) and while feeding (e.g. pausing during a feeding bout to observe).

Data analysis

Observational data were tabulated. Tables document how many black cockatoos were seen, when and where, and whether they were feeding or roosting.

Analysis of vegetation structure and floristics followed Catterall *et al*. (2004) with (1) an initial graphical presentation, accompanied by univariate statistics, and (2) multivariate analysis comparing vegetation structure and floristics between pits and between interior and exterior plots.

Initially, the means of the structural variables (canopy cover, canopy height, non-canopy and stem density (living and dead)) were used as dependent variables in two-way ANOVA (after confirming assumptions such as homoscedascity and normality) with factors of Pit (the nine pits) and Location (interior or exterior plots). The significance level for main effects and interactions was set at 0.01 to allow for the multiple tests. When significant, ANOVA was followed with Tukey's HSD tests.

Structural differences were explored further using two-way non-parametric multivariate analysis of variance (PERMANOVA), based on the Bray–Curtis distance measure (for a justification, see Clarke and Warwick 2001). This non-parametric analogue to traditional MANOVA tests the significance of all factors and interactions (Anderson 2001). The factors were Pit (the nine rehabilitation pits) and Location (the interior and exterior plots). Before analysis we range-standardised each variable between 0 and 1 by subtracting the smallest score from each value and dividing the result by the difference between the largest and the smallest score, allowing an equal impact of variables irrespective of measurement scale. While *post hoc* tests could be used to compare individual pits, we did not use them because the pits were not different experimental treatments. We were most interested in whether pits were similar overall, rather than details of any differences. Instead, where PERMANOVA was significant, we used similarity percentage (SIMPER) (Clarke and Warwick 2001) to determine contribution of individual plant species to the difference. We used program PAST for all analyses (Hammer *et al*. 2001).

We compared floristics between interior and exterior plots and across the nine rehabilitation pits using two-way PERMANOVA, followed by SIMPER if factors in the PERMANOVA were significant. The dependent variables were the number of live stems of 16 food plant species counted in each plot. Range-standardisation was unnecessary because each species was assessed using stem number.

Use of food plant species by black cockatoos, determined by feeding residues, was represented with bar graphs. These showed the total plots containing residues from each food plant species in each sampling occasion summed across pits, and in each pit summed across all sampling occasions.

Statistical significance of differences in feeding between pits and between interior and exterior plots across pits on each sampling occasion was determined using two-way PERMANOVA, with factors of Pit (nine rehabilitation pits) and Location (interior and exterior plots). The dependent variables were the range-standardised feeding residues for each food species. Where PERMANOVA was significant, we used SIMPER to determine the contribution of individual plant species.

Lastly, we used PERMANOVA to compare the vegetation characteristics for plots where feeding did or did not occur. We used data from the first sampling occasion only, because only phenological variables might differ markedly across the three sampling occasions. The factors were Pit (nine rehabilitation pits) and Location (interior and exterior plots). The dependent variables are indicated in Table 1.

Results

Structure and floristics of the vegetation in the pits

In two-way ANOVA all structural variables differed significantly ($P < 0.001$) across pits except for average canopy height ($P = 0.10$). Only canopy cover and stem density (dead) differed ($P < 0.001$) between interior and exterior plots. Both were higher in interior plots. There were no significant interactions ($P \geq 0.29$ in all cases) (Fig. 3). PERMANOVA found significant structural differences across pits and between exterior and interior plots, but no interaction (Table 2). SIMPER indicated that average non-canopy height (23.8%) and canopy cover (23.5%) explained almost half the differences across pits, and that canopy cover (23.7%) and average non-canopy height (23.0%) explained almost half of the differences between interior and exterior plots (Table 2).

PERMANOVA found significant differences in floristics across pits, but not between exterior and interior plots. The interaction was not significant (Table 2). SIMPER indicated that the number of live stems of marri (28.8%), number of live stems of *Hakea undulata* (15.2%) and number of live stems of jarrah (15.0%) caused nearly 60% of the differences across pits (Table 2).

Patterns of feeding activity revealed by feeding residues

We found feeding residues in most plots. In the first and second sampling sessions, feeding residues from *B. squarrosa*, marri and *H. undulata* occurred most frequently (summed across all pits) (Fig. 4). In the third sampling session, feeding residues from marri and *B. squarrosa* occurred most frequently (summed across all pits). Combining results across all sampling sessions, the number of species with feeding residues present in a pit ranged from one (WTR) to eight (L2 and Q1). The species frequency of feeding residues differed across pits, with *H. undulata* feeding residues being most frequent in two pits, marri in three, *B. squarrosa* in three and *B. sessilis* in one (Fig. 5).

On all sampling occasions, PERMANOVA found significant differences in black cockatoo feeding activity (as measured by feeding residues) across pits, but not between exterior and interior plots. Interactions were not significant (Table 2). SIMPER revealed that the food plants mainly causing the differences were *B. squarrosa* (29.0%), *H. undulata* (20.1%) and marri (11.6%) on the first occasion, *B. squarrosa* (22.5%), *H. prostrata* (22.4%) and *H. undulata* (18.3%) on the second, and marri (50.9%) on the third (Table 2).

Feeding on marri

Baudin's cockatoos had fed on almost every marri tree with feeding residue (Tables 3, 4). FRTBC fed on fewer marri trees across the three sampling sessions (Table 3) and across the different pits (Table 4).

Comparisons of feeding and non-feeding plots

There was no significant difference between feed and non-feed plots in a range of structural and floristic variables ($F_{34,55} = 1.58$, $P = 0.12$) (Table 2).

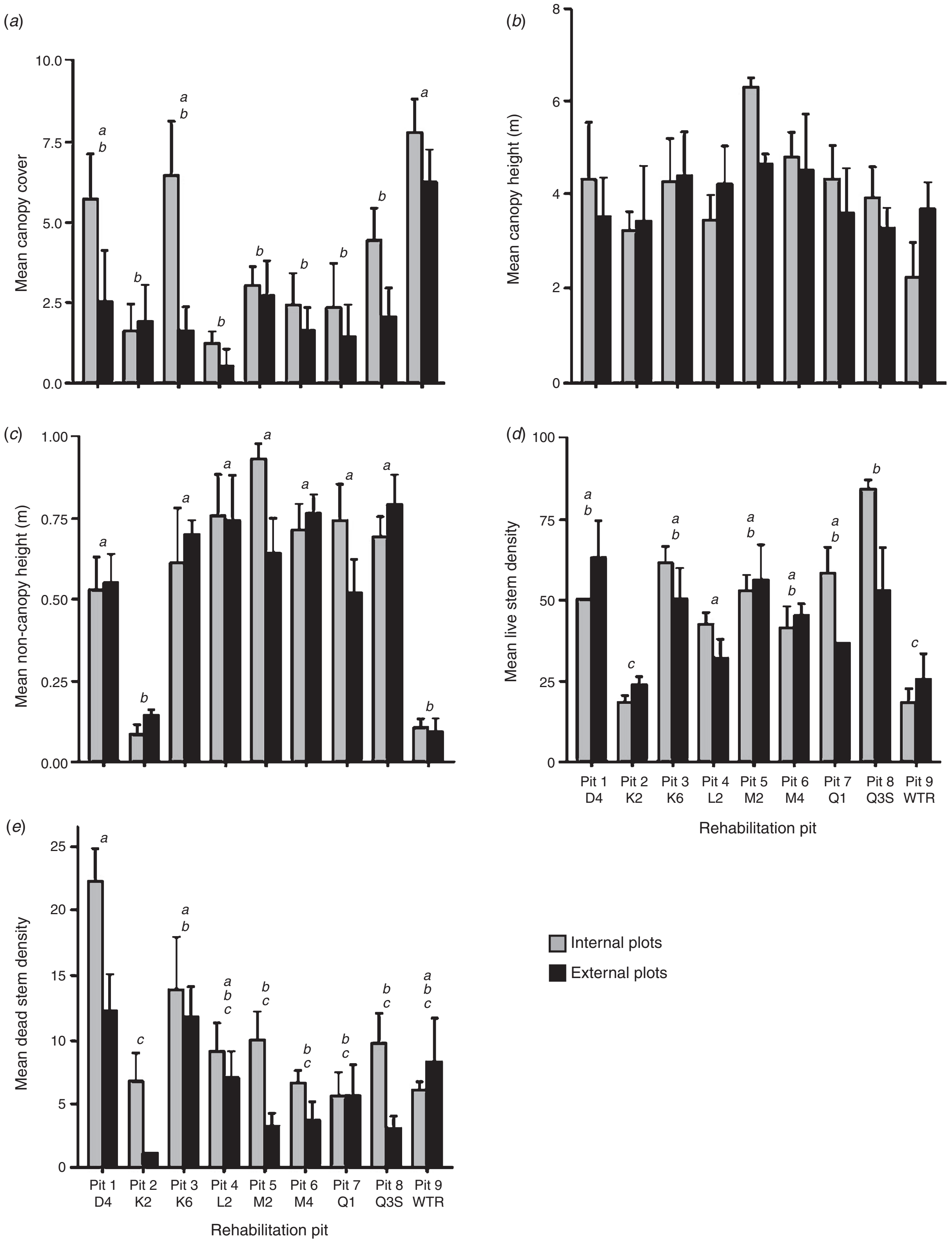

Fig. 3. Mean canopy cover, mean canopy height, mean non-canopy height, mean stem density (live), and mean stem density (dead) (*a*) – (*e*) for interior and exterior plots at each of nine rehabilitation pits. The stem densities in (*d*) and (*e*) represent the mean number of live or dead trees per plot, respectively. Error bars are standard errors. Pits differing significantly in mean values at the 5% level using Tukey's HSD are shown with superscripts. There were no significant interactions between interior/exterior plots and pits.

Table 2. Results of multivariate statistical tests of six questions regarding vegetation structure and floristics across rehabilitation pits and patterns of black cockatoo feeding

SIMPER (similarity percentage) indicates the percentage contribution made by the named variable to the significant difference observed. The table lists the variables contributing most to variability up to the first 50% of variability observed

Research question	Results of PERMANOVA	Variables contributing most to significant effects in SIMPER (where PERMANOVA is significant)
Does vegetation structure vary across pits or between interior and exterior plots?	Pit: $F_{8,89} = 8.91$, $P < 0.001$	Pits: non-canopy height – 23.8%; canopy cover – 23.5%
	Interior/exterior plots: $F_{1,89} = 5.40$, $P < 0.001$	Interior/exterior plots: canopy cover – 23.7%; non-canopy height – 23.0%
	Interaction: $F_{8,89} = 1.13$, $P = 0.30$	
Do floristics vary across pits or between interior and exterior plots?	Pit: $F_{8,89} = 6.69$, $P < 0.001$	Pits: no. of live stems of marri – 28.8%; no. of live stems of *H. undulata* – 15.2%; no. of live stems of jarrah – 15.0%
	Interior/exterior plots: $F_{1,89} = 1.26$, $P = 0.26$	
	Interaction: $F_{8,89} = 1.08$, $P = 0.32$	
Did black cockatoo feeding residues vary across pits or between interior and exterior plots on the first sampling occasion?	Pit: $F_{8,89} = 4.04$, $P < 0.001$	Pits: *B. squarrosa* – 29.0%; *H. undulata* – 20.1%; Marri – 11.6%
	Interior/exterior plots: $F_{1,89} = 1.00$, $P = 0.39$	
	Interaction: $F_{8,89} = 0.75$, $P = 0.87$	
Did black cockatoo feeding residues vary across pits or between interior and exterior plots on the second sampling occasion?	Pit: $F_{8,89} = 3.53$, $P < 0.001$	Pits: *B. squarrosa* – 22.5%; *H.* prostrata – 22.4%; *H. undulata* – 18.3%
	Interior/exterior plots: $F_{1,89} = 1.26$, $P = 0.26$	
	Interaction: $F_{8,89} = 1.66$, $P = 0.24$	
Did black cockatoo feeding residues vary across pits or between interior and exterior plots on the third sampling occasion?	Pit: $F_{8,89} = 3.28$, $P < 0.001$	Pits: marri – 50.9%
	Interior/exterior plots: $F_{1,89} = 0.80$, $P = 0.48$	
	Interaction: $F_{8,89} = 0.98$, $P = 0.47$	
Did vegetation structure and the floristics of major food plants vary between feed and non-feed plots for black cockatoos?	$F_{34,55} = 1.58$, $P = 0.12$	Not applicable

Observations of black cockatoos in rehabilitated mine pits

We recorded 52 visual or acoustic detections of black cockatoos during low-level monitoring. Carnaby's cockatoo was the most frequently detected species ($n = 28$ of 52 detections, 53.8%), followed by Baudin's cockatoo ($n = 13$ of 52 detections, 25%) and FRTBC ($n = 11$ of 52 detections, 21.1%) (Table 5).

We saw Carnaby's cockatoos ($n = 25$ sightings, 71.4%) and Baudin's cockatoos ($n = 10$ sightings, 28.6%) feeding or roosting in rehabilitation vegetation. These sightings occurred during low-level monitoring ($n = 10$) and opportunistic encounters ($n = 25$). Birds were mainly feeding ($n = 21$ sightings, 60%) or short-term roosting ($n = 12$ sightings, 34.3%). Carnaby's cockatoos fed on proteaceous shrubs (*Hakea* or *Banksia* spp.) ($n = 11$ sightings), forest sheoak (*Allocasuarina fraseriana*) ($n = 1$ sighting), radiata pine (*Pinus radiata*) ($n = 1$ sighting), and jarrah ($n = 1$ sighting). We also observed Carnaby's cockatoos feeding on the ground among the rehabilitation vegetation, but could not determine the food source. We observed Baudin's cockatoos feeding only on marri ($n = 8$ sightings). We did not see FRTBC using rehabilitation vegetation, although we did see them feeding on native vegetation directly adjacent.

Group sizes for Carnaby's cockatoos ranged from one to 72 individuals, with a mean of 13.2 ± 3.2 birds and a median of 8 (25% = 3.3; 75% = 19). Group sizes for Baudin's cockatoos ranged from three to 107 individuals, with a mean of 20.6 ± 9.8 birds and a median of 13 (25% = 7.5; 75% = 18.5) ($n = 10$ sightings).

Discussion

Black cockatoos began feeding in rehabilitated pits within eight years. Proteaceous and myrtaceous foods were both important. Behavioural observation, assessment of feeding residues, and vegetation sampling were complementary in investigating feeding and, critically, in documenting feeding by FRTBC. Such a multipronged approach is applicable for investigating feeding by other large, mobile species that occur at low densities.

Structure and floristics of the vegetation in the pits

Vegetation in rehabilitated pits varied structurally and floristically despite common (with the exception of 'WTR') rehabilitation prescriptions. Variation in the trajectory of mine-site rehabilitation is common (Brady and Noske 2010). Most pits had thick, proteaceous understorey under an open canopy, characteristic of early-successional-stage rehabilitation in the region (Norman *et al.* 2006).

Patterns of feeding activity revealed by feeding residues

We found feeding residues in most sampling plots and across all pits. Residues were observed from eight proteaceous species and two myrtaceous species, demonstrating the diversity of food plants available, particularly *Banksia* and *Hakea* shrubs. New feeding residues in the second and third sampling occasions confirmed year-round feeding.

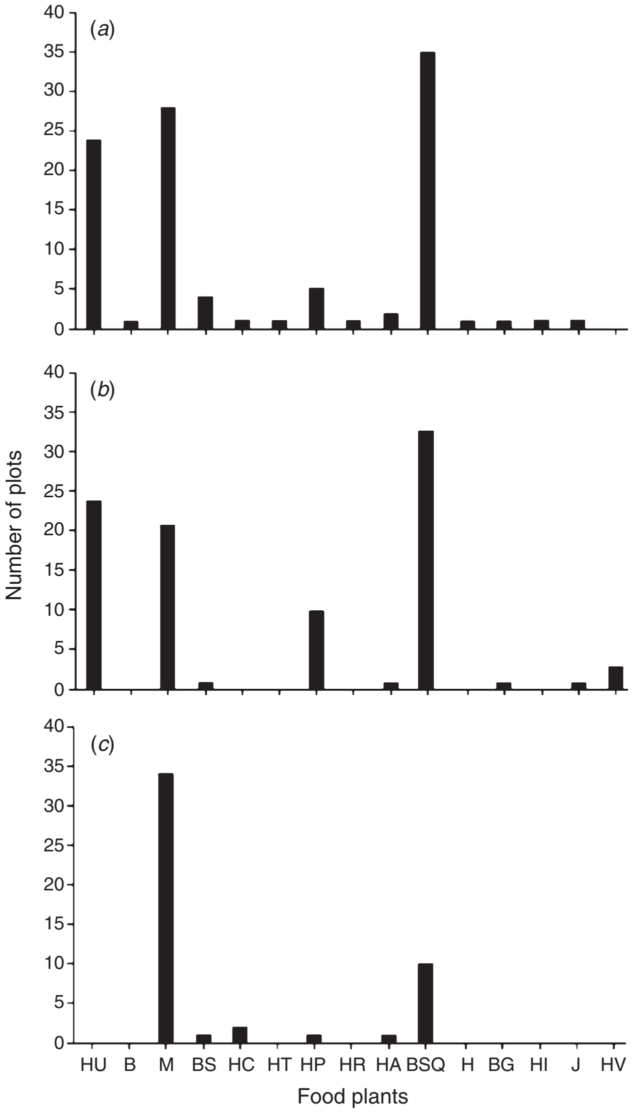

Fig. 4. The number of plots containing residues of particular food plant species observed across all pits for each of three sampling sessions: (*a*) winter 2009, (*b*) summer 2010 and (*c*) winter 2010. Legend: HU, *Hakea undulata*; D, *Banksia* spp.; M, *Corymbia calophylla*; DS, *B. sessilis*; HC, *H. cyclocarpa*; HT, *H. trifurcata*; HP, *H. prostrata*; HR, *H. ruscifolia*; HA, *H. amplexicircus*; DSQ, *B. squarrosa*; H, *Hakea* sp.; BG, *B. grandis*; J, *Eucalyptus marginata*; HV, *H. varia*.

Marri feeding residues confirmed that FRTBC do feed within the rehabilitated mine pits, although the lower abundance of residues for FRTBC implies that FRTBC feed less in the pits than the other species. Lower feeding activity cannot be attributed to lower abundance, as FRTBC were detected more frequently than Baudin's cockatoos and Carnaby's cockatoos during site-wide surveys at NBG (Lee *et al*. 2013) and in similar frequencies to Baudin's cockatoos during low-level monitoring of pits in this study. FRTBC may be more sensitive to predation risk (Weerheim 2008), and therefore avoid open habitats, as is known for black cockatoos elsewhere (Chapman and Paton 2005; Cameron and Cunningham 2006). If so, FRTBC may begin using pits more at a later successional stage.

Although the vegetation in the pits was at an early successional stage, four species – marri, *H. undulata*, *H. prostrata* and *B. squarrosa* – accounted for most feeding residues, consistent with the feeding habits of black cockatoos in south-western Australia (Saunders 1980; Johnstone and Storr 1998; Johnstone and Kirkby 1999, 2008; Chapman 2007; Biggs *et al*. 2011; Lee *et al*. 2013). Feeding residues were not recorded for forest sheoak despite their abundance. FRTBC do feed on *Allocausuarina* spp. (Johnstone and Kirkby 1999) and it is unclear why they did not do so in the rehabilitation pits, where cones were observed. Similarly, there were far fewer feeding residues of jarrah than of marri, despite others finding more even use of the two species (e.g. Johnstone and Kirkby 1999; Biggs *et al*. 2011). We do not have data on the quality or percentage of the available seed crop that was foraged, so we are unable to determine whether the revegetated pits were providing an excess of food or were being used to capacity.

Differences in feeding across pits may relate to variation in food plants. Despite the same rehabilitation approach and seed mix being applied, plant survival differed between pits, leading to differences in the relative proportions of species and also in density, which was reflected in the significant differences in floristics and structure across pits. This variability is common in early-stage mine-site rehabilitation, with sites becoming more similar as vegetation ages (Brady and Noske 2010).

Comparisons of feeding and non-feeding plots

We found no statistically significant differences in vegetation characteristics between plots where feeding occurred and plots where residues were absent. Birds probably consider other factors, such as pit location, in choosing where to feed. Black cockatoos may prefer particular pits because of their proximity to nesting or roosting sites, thereby reducing the energy spent in travelling (Chapman and Paton 2005). In addition, large (>50 birds) flocks of Carnaby's cockatoos and Baudin's cockatoos visit NBG during seasonal migrations (Lee *et al*. 2013) and, given their size, may influence patterns of feeding activity. As these flocks are likely to feed on plants flowering or seeding at the time, phenology may be important.

Both myrtaceous and proteaceous species produce food (seed, flowers) in predictable seasons in Western Australia, although the quantity of flowers and seed may vary (Marchant *et al*. 1987). The reproductive cycle of marri and jarrah depends on environmental conditions and individual trees may flower only every few years (Nichols and Watkins 1984), so the availability of seed from marri and jarrah varies annually. The rehabilitation prescriptions at NBG, such as fertiliser, may encourage stronger growth and productivity and different phenological patterns compared with plants in native forest.

Observations of black cockatoos in rehabilitated mine pits

While low-level monitoring confirmed that all three species occurred in the vicinity of the pits, observational approaches were unable to confirm that FRTBC use rehabilitation vegetation for feeding or roosting. Feeding residues were effective for species detection. They obviate reliance on more intensive observational approaches, such as flock (group) follows (Altmann 1974), to confirm species recolonisation.

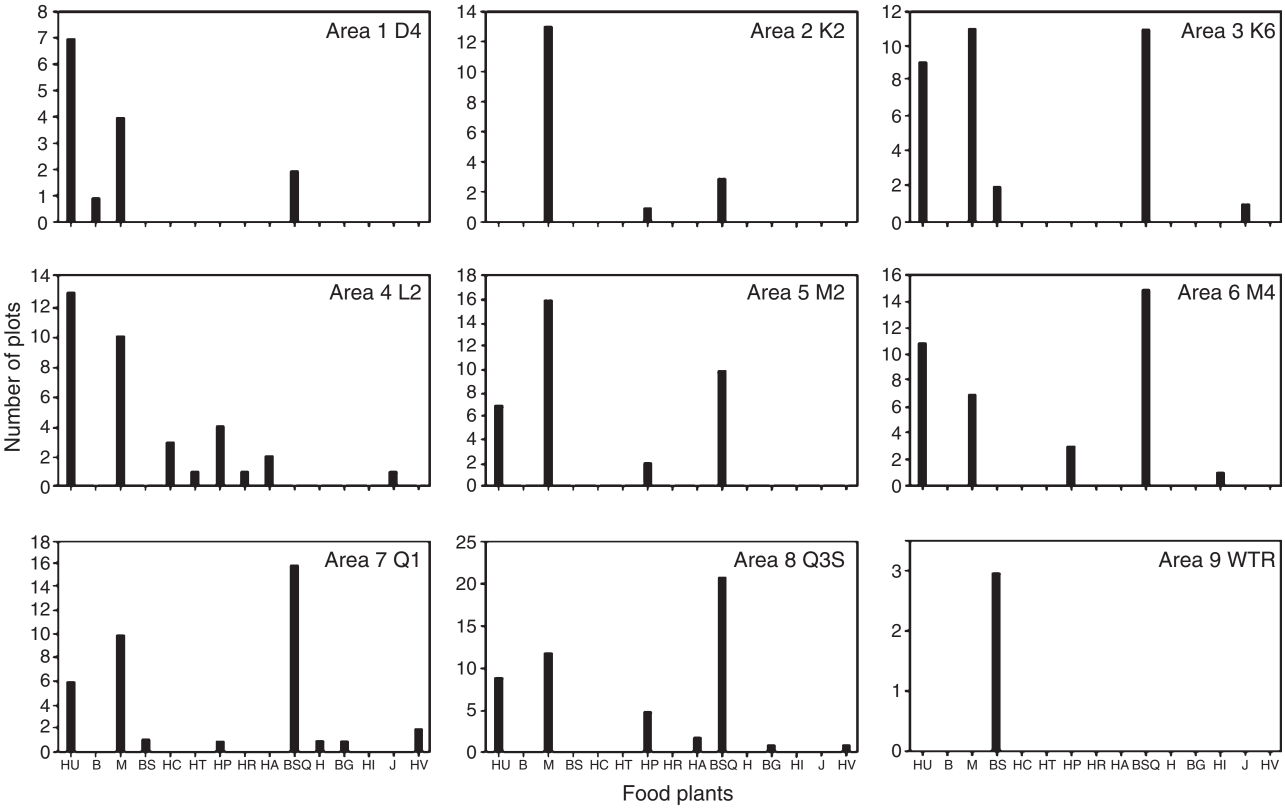

Fig. 5. The number of plots containing residues of particular food plant species observed in each pit across all three sampling sessions: (*a*) winter 2009, (*b*) summer 2010 and (*c*) winter 2010. The legend is given in Fig. 4.

Table 3. The total number of marri trees where feeding residues were detected (i.e. 'feed trees') for different sampling occasions

The number of trees where those residues could be attributed to Baudin's Cockatoos or FRTBC is also shown. Some trees contained residues from both species, so the total number of trees with feeding residues present is less than the sum value of feed trees for the two species. The percentages represent the number of feed trees for each species divided by the total number of feed trees observed for each season

Sampling occasions	Baudin's cockatoo	Forest red-tailed black cockatoo	Total
Winter 2009	54 (98.2%)	8 (14.5%)	55
Summer 2009–10	34 (97.1%)	5 (14.3%)	35
Winter 2010	66 (100%)	3 (4.5%)	66
Total	154 (98.7%)	16 (10.4%)	156

Birds used rehabilitation sites mainly for feeding. Short-term roosting was associated with feeding or stop-over movements. The canopy-forming trees in the pits had high stem densities, low heights (<10 m) and narrow canopies (<5 m across), so birds may prefer roosting for longer periods in mature trees in adjacent forest where mature trees measuring >15 m high are widely available (Biggs *et al*. 2011). Group sizes of Baudin's cockatoos and Carnaby's cockatoos within rehabilitated mine pits were similar to those reported by Lee *et al*. (2013) for these species at NBG and surrounds.

Table 4. The total number of marri trees where feeding residues were detected (i.e. 'feed trees') for different rehabilitated mine pits

The codes for the pits correspond to the pit locations in Fig. 1. 'est' refers to the year when revegetation commenced. The number of trees where those residues could be attributed to Baudin's Cockatoos or FRTBC is also shown. Some trees contained residues from both species, so the total number of trees with feeding residues present is less than the sum value of feed trees for the two species. The percentages represent the number of feed trees for each species divided by the total number of feed trees observed for each pit

Pits	Baudin's cockatoo	Forest red-tailed black cockatoo	Total
D4 (est. 1996)	9 (90.0%)	1 (10.0%)	10
WTR (est. 1998)	0	0	0
K2 (est. 2000)	25 (96.2%)	3 (11.5%)	26
K6 (est. 2000)	19 (100%)	3 (15.8%)	19
L2 (est. 2001)	13 (100%)	2 (15.4%)	13
M2 (est. 2001)	40 (100%)	0	40
M4 (est. 2001)	16 (100%)	1 (6.3%)	16
Q1 (est. 2002)	13 (100%)	4 (30.8%)	13
Q3S (est. 2002)	19 (100%)	2 (10.5%)	19
Total	154 (98.7%)	16 (10.3%)	156

Management implications

Establishing proteaceous food plants and marri provides feeding habitat for threatened black cockatoos quickly, emphasising benefits of planting black cockatoo food plants across the region

Table 5. Number of occasions that one of the three black cockatoo species was detected, either visually or acoustically, within the immediate vicinity of a rehabilitated mining pit during systematic surveys of 23 pits over 22 months of sampling

Pit	Carnaby's cockatoo	Baudin's cockatoo	Forest red-tailed black cockatoo
1	3	0	1
2	1	0	0
3	3	0	0
4	4	0	0
5	1	0	1
6	1	1	0
7	3	0	0
8	2	0	0
9	0	0	1
10	0	0	0
11	2	0	0
12	0	2	0
13	0	1	0
14	0	1	0
15	0	2	1
16	0	1	0
17	1	0	0
18	1	2	0
19	1	0	1
20	0	0	1
21	1	0	1
22	0	1	2
23	4	2	2
Total	28	13	11

(Hobbs and Saunders 1993; Whisenant 1999; Hobbs and Lambeck 2002). However, while black cockatoos returned to a revegetated landscape, the equivalence of the re-established vegetation with native forest is unknown (Gould 2011). At NBG, the aim of rehabilitating mine pits was to establish a vegetation community similar to the surrounding native forest, which takes decades to achieve (Koch and Hobbs 2007). Thus, demonstrating feeding activity within early successional revegetation represents only the initial step. Equivalency to undisturbed native vegetation must be assessed at appropriate time-scales, requiring comparative information on food plant quality and availability. For example, the productivity of newly established revegetation may be higher than that of surrounding mature forest because proteaceous shrubs predominate before being shaded out by the developing myrtaceous canopy (although we did not compare rehabilitated pits and native forest in this study).

Revegetation efforts should also consider the comparative importance of native vegetation and revegetation at a landscape scale. In highly fragmented landscapes, such as portions of the wheatbelt, tracts of revegetation could support successful breeding given the lack of native food plants near nest sites (Saunders and Ingram 1987). Where significant remnant vegetation remains, as at NBG, revegetation may be less significant. Many areas of revegetation are also small and may not sustain many birds. Rehabilitation areas at NBG, for example, cover less than 200 ha, whereas the surrounding landscape includes contiguous native forest to the north, south, and west as well as a large (>3000 ha) pine (*Pinus radiata*) plantation to the north-east (Fig. 1).

Revegetation strategies should also consider the prevailing patterns of vegetation succession, given site conditions and the plant species used (Norman *et al*. 2006; Walker *et al*. 2007). In many landscapes in Australia proteaceous species mature faster than myrtaceous species and establish a thick shrub layer. At NBG, this shrub layer provided proteaceous seeds and flowers for black cockatoos. The availability of proteaceous food plants is particularly important because of the apparent time lag before birds begin feeding on jarrah seed, a common food for all three black cockatoos (Saunders 1980; Johnstone and Kirkby 2008; Biggs *et al*. 2011; Lee *et al*. 2013). Regenerating marri, though fed upon, does not have the large canopy volumes (and therefore abundant food) of mature trees.

As the rehabilitation vegetation at NBG ages, proteaceous plants should decline as myrtaceous trees mature and form a stronger canopy (Williams and Woinarski 1997). Feeding on myrtaceous species by Baudin's cockatoos (and possibly also FRTBC) may increase and feeding on proteaceous species by Carnaby's cockatoos may become less common. This suggests two possible strategies for restoring feeding habitat for black cockatoos: (1) use proteaceous or myrtaceous species to maintain a steady supply of particular food plants, or (2) use a mixed-strategy employing both proteaceous or myrtaceous species, recognising that succession will change the mix of food plants over time. Such strategies need to be compatible with other restoration goals for mining pits.

Climate change models predict higher temperatures and reduced rainfall in much of the south-west, with effects already being seen (Matusick *et al*. 2013), so choice of plants for revegetation may need to consider drought tolerance (Lee *et al*. 2013), especially considering the susceptibility of black cockatoos to heat-related stress (Saunders *et al*. 2011). Additionally, tree hollows suitable for breeding may take over a century to form, so conservation of old, hollow-bearing trees is an essential complement to restoring food plants (Abbott and Whitford 2002).

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