Landscape position predicts distribution of eucalypt feed trees for threatened black-cockatoos in the northern jarrah forest, Western Australia

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Abstract

The Jarrah forest of southwestern Australia supports mineral and timber production and provides important food plants for three threatened black-cockatoo species. To assist the integration of conservation and production objectives, we studied the landscape distribution of two important black-cockatoo food sources, the eucalypts Jarrah *Eucalyptus marginata* and Marri *Corymbia calophylla*, at a mine site in the northeastern Jarrah forest in 2008. Jarrah and Marri were not distributed randomly across the landscape. Stem densities of Jarrah and Marri were highest on lower slopes and on ridgetops respectively, while stem densities for both species were lowest in lowland areas, where stems of Wandoo (*E. wandoo*) often occurred. The distribution of Jarrah and Marri 'feed trees' used by cockatoos did not follow this landscape pattern, with Marri feed trees showing a distinct association with lower slopes and lowland areas, and Jarrah feed trees more evenly distributed across landscape positions. Multiple logistic regression with biotic (stem densities), topographical (landscape position), and disturbance (*e.g.* presence of cut stumps) variables indicated that feed trees were most likely to occur on lowlands and lower slopes in the absence of Wandoo. Although Jarrah and Marri occurred at a frequency ratio of 3:1, a significantly higher proportion of Marri trees (13.0%) were used as feed trees than were Jarrah trees (5.2%). These findings suggest that Marri is likely the more important food source at a landscape-scale, but longer-term studies are needed to rule out the possibility that the relative importance of the different tree species varies seasonally and inter-annually.

Keywords: black-cockatoos, Jarrah, Marri, Jarrah forest, landscape, *Calyptorhynchus*

Introduction

Carnaby's Cockatoo *Calyptorhynchus latirostris*, Baudin's Cockatoo *C. baudinii*, and Forest Red-tailed Black-cockatoo (FRTBC) *C. banksii naso* (a subspecies) from southwestern Australia are listed as threatened species under the Commonwealth *Environmental Protection and Biodiversity Conservation Act 1999*. All three black-cockatoos range within the region's remaining forest habitats, and two (Baudin's Cockatoos and FRTBC) feed almost exclusively on forest-based food sources (Saunders 1980; Johnstone & Storr 1998; Johnstone & Kirkby 1999, 2008). Therefore the conservation of forest feeding habitats is a priority for species recovery, particularly in the Jarrah forest, which is the region's largest forest habitat (Chapman 2007a).

Much of the Jarrah forest lies outside formal reserves, so habitat conservation requires sympathetic management and restoration practices by mining and timber production, the two major land uses within the Jarrah forest (Abbott 1998, Wardell-Johnson *et al.* 2004, Chapman 2007a, Lee *et al.* 2010). Approximately 800 000 ha of the Jarrah forest is available for timber harvesting (Conservation Commission 2004). While individual

mining operations are much smaller [*e.g.*, the operations of Alcoa Alumina have affected about 13 000 ha of forest (Koch 2007)], much of the Jarrah forest is subject to mining or exploration leases under State Agreement Acts or other State legislation, allowing for on-going expansion of existing operations (RFA 1998).

Studies of crop contents and observations of feeding behaviour indicate that two eucalypt species (Jarrah *Eucalyptus marginata* and Marri *Corymbia callophylla*) are the main food sources for black-cockatoos in southwestern Western Australia forests (Saunders 1974a, 1980; Johnstone & Kirkby 1999, 2008). This reflects characteristics of their fruits and the fact that the two eucalypts are the dominant over-storey species across the extent of the Jarrah forest, occurring at a ratio of between 2:1 to 9:1 depending on location, slope position and silvicultural practices (Pryor 1959; Abbott & Loneragan 1986; Whitford 2002; Koch & Samsa 2007).

Baudin's Cockatoos are considered Marri specialists, although they also eat insect larvae, orchard fruit, and other plants (Saunders 1974b; Johnstone & Storr 1998; Cale 2003; Chapman 2007b; Johnstone & Kirkby 2008). Baudin's Cockatoos also feed on the buds and flowers of *Banksia* spp. and *Eucalyptus* spp. (Johnstone & Kirkby 2008). Marri and Jarrah seeds comprise around 90% of the diet of FRTBC, although they also feed on the seeds of

other eucalypts, as well as those of Sheoak *Allocasuarina fraseriana* and Snottygobble *Persoonia longifolia* (Robinson 1960; Johnstone & Storr 1998; Johnstone & Kirby 1999; Cooper *et al*. 2003). However, on-going research suggests that the foraging ecology of FRTBC has changed over the past 12 years, including changes in the proportions of different food plants (Ron Johnstone and Tony Kirkby, Western Australian Museum, unpublished data). Carnaby's Cockatoos also feed within forested areas, although their diet is more varied, including seeds and nectar of Jarrah, Marri, *Banksia* spp., *Hakea* spp., and *Pinus* spp. taken mainly from proteaceous scrubs and heathland, eucalypt forests and woodlands, and pine plantations (Saunders 1974a,b; Saunders 1980).

Landscape position is likely to influence where black-cockatoos feed on Jarrah and Marri within the Jarrah forest (Abbott 1998). The Jarrah forest's undulating topography is characterised by bauxitic uplands and alluvial lowlands, leading to substantial differences in soil texture, nutrient availability, and moisture content across landscape positions, and ultimately to differing vegetation types and plant productivities (Churchill 1968; Mulcahy *et al*. 1972; Havel 1975a,b; Dell *et al*. 1989). While Jarrah and Marri occur in all slope positions within the Jarrah forest, Marri is most productive in lowland areas with alluvial soils (Lane-Poole 1920, Boland *et al*. 1984), while Jarrah is often absent or rare in valleys and along drainage lines (Mattiske & Havel 1998, Havel 2000). Therefore Jarrah and Marri trees used as 'feed trees' by black-cockatoos may have predictable, and perhaps differing, distributions across landscape positions within the Jarrah forest (Abbott 1998). Patterns in the use of Jarrah and Marri trees, if present, may vary seasonally and inter-annually in response to environmental conditions and to flowering and fruiting cycles for Jarrah and Marri. Site- and landscape-scale variation may also occur because of differences in rainfall patterns and disturbances such as logging, fire history, and plant disease (Garkaklis *et al*. 2004).

We studied the foraging ecology of black-cockatoos at a mine site along the eastern margin of the northern Jarrah forest that also had a history of logging. Our objectives were to: (i) determine where in the landscape Marri and Jarrah trees and 'feed trees' occurred; (ii) assess whether landscape position, stem densities, or measures of disturbance from fire and logging best predicted the occurrence of 'feed trees'; and (iii) evaluate the implications of the findings for conserving black-cockatoo feeding habitat within areas used for timber and mineral production.
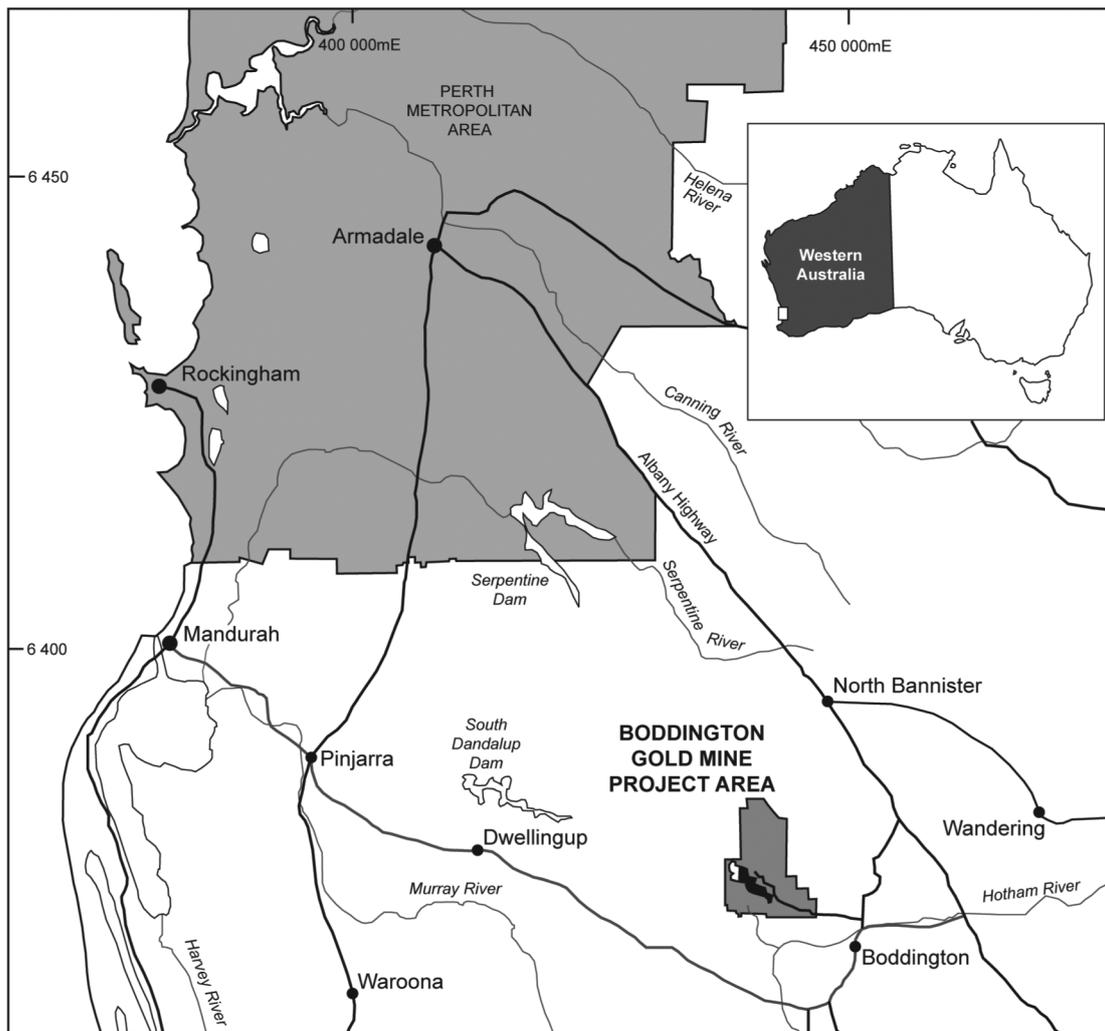
Figure 1. The location of the study site near Boddington, southwestern Australia.

Methods

Study area

The study site was located within mining tenements for Newmont Boddington Gold (NBG) (Figure 1). The NBG study site lies between the 700 mm and 800 mm isohyets on the eastern boundary of the northern Jarrah forest subregion on highly leached soils of the Darling Plateau (Dell *et al*. 1989, Rayner *et al*. 1996), near the ecotone along the eastern margin of the Jarrah forest shifting towards Wandoo woodland further east. The vegetation is mainly open eucalypt forest, with the upper-storey dominated by Jarrah interspersed with varying admixtures of Marri and Wandoo Eucalyptus wandoo, a middle-storey sometimes comprised of Bull Banksia (*Banksia grandis*) and Sheoak (*Allocasuarina fraseriana*) and a shrub layer of proteaceous and other shrubs (Dell *et al*. 1989). Sandy soils along upper slopes are associated with the presence of Sheoak and moist, fertile soils with Marri (Worsley Alumina Pty Ltd. 1999). The site was first logged in the early 1900s and has been logged at least twice since (Heberle 1997). Gold-mining operations began at the site in 1987 (Rayner *et al*. 1996).

All three black-cockatoo species were recorded within the sampling area during this study and in the course of a longer-term study from 2007–2010 (Lee *et al*. 2010; J. Lee and H. Finn, Murdoch University, unpublished data). While Carnaby's Cockatoos and FRTBC are present year-round at NBG in small numbers, larger abundances of Carnaby's Cockatoos also occur in spring and autumn as birds migrate between Wheatbelt breeding sites and feeding areas on the Swan Coastal Plain. Baudin's Cockatoos peak in abundance from April–September (J. Lee and H. Finn, Murdoch University, unpublished data). Nest sites for Carnaby's Cockatoos and FRTBC occur within or near to NBG (J. Lee and H. Finn, Murdoch University, unpublished data). NBG is considered outside the historic breeding range of Baudin's Cockatoos, with the species breeding in the Karri forest and southern Jarrah forest, although recent observations of breeding Baudin's Cockatoos in the northern Jarrah forest indicate breeding ranges may be changing (Johnstone & Kirkby 2008, 2009).

Field sampling

Six sampling locations (hereafter sites) were positioned across a diversity of landscape elements in accordance with the recommendations of Wardell-Johnson and Horwitz (1996). At each site, transect lines running parallel with the slope contour were positioned at four positions in the landscape: lowland (valley floor), lower-slope, upper-slope, and ridge-top. The transect lines varied from 420 m to 1400 m (mean transect length = 1103 m), with transect length determined by the topography of each site. Systematic plots (20 m x 20 m) were sampled at 200 m intervals along each transect (*i.e.* 0 m, 200 m, 400 m, *etc*.). Plots began at the interval point and extended for 20 m down the transect line and 10m to either side of the transect line. Plots were also established around any feed trees (recognised by the presence of feeding residues) encountered within 5 m to either side of the transect line. Thus, the basic sampling unit was a single transect located in one of four landscape elements and the plots represented sub-sampling within a transect. A further

24 plots were also sampled along transects for other purposes (*e.g.* presence of potential nest hollow).

Sampling occurred in April to July 2008. We recorded 10 variables for each plot on each occasion for use in assessing possible predictors of feeding activity: (a) landscape position (transect location: lowland, lower-slope, upper-slope or ridge-top); (b) number of woody stems [no. of woody stems >6m tall for the five dominant over- and mid-storey plants at the site: Jarrah, Marri, Wandoo, Sheoak and Bull Banksia]; and (c) four disturbance variables [presence or absence of fallen logs, cut stumps, logging track, fire scars].

Feeding residues and feed-tree plots

Different species of black-cockatoos leave characteristic markings on residues at feeding sites (Johnstone & Kirkby 1999, Cooper 2000, Cooper *et al*. 2003, Weerheim 2008), which we used to identify feed trees. We focused on the two upper-storey species Marri and Jarrah because: they are the main food plants for black-cockatoos in forest areas (with some exceptions, *e.g.* seeds and flowers of *Banksia* spp. may be critical foods at certain sites or during certain periods); their feeding residues are persistent; and they were the most abundant tree species in the area. We recorded whether Jarrah and Marri feeding residues were obviously 'old' (>1 year-old), based on colouring (*e.g.* grey, faded) and condition (*e.g.* deteriorated). FRTBC shear the base of Marri fruits at a 45º angle to remove seeds (the 'bottomslice' method), while Baudin's Cockatoos use their elongated upper mandible to pry seeds out, leaving the fruit intact (the 'lever') (Johnstone & Kirkby 1999, Cooper 2000, Cooper *et al*. 2003, Weerheim 2008).

Carnaby's Cockatoos may use either technique to feed on Marri fruit, but generally with some modification, *e.g.* the 'slicing' of fruits may occur along the side of the fruit casing (H. Finn, Murdoch University, unpublished data). The 'levering' of Marri fruits by Carnaby's Cockatoos tends to leave different marks on the fruit casings, particularly in the location of indentations by the lower mandible and in the amount of damage caused to the rim of the fruit casing. Carnaby's Cockatoos also generally feed on green Marri fruits that are soft enough for their beaks to manipulate. Observations of Carnaby's Cockatoos feeding on Marri at NBG are very infrequent (*i.e.* one observation out of more than 150 observations of Carnaby's Cockatoos at NBG between November 2007 and April 2010; J. Lee and H. Finn, Murdoch University, unpublished data). For these reasons—differences in markings on fruits and lack of observations—we attributed Marri feeding residues either to Baudin's Cockatoos or to FRTBC.

We do not consider Bull Banksia feeding residues in this study for two reasons: (1) the taking of seeds or nectar *in situ* often leaves no clear diagnostic marking on the cone or flower spike and (2) feeding marks on flower spikes (where present) becomes difficult to discern once the spikes have fallen to the ground. Likewise, Sheoak feeding residues degrade quickly, and thus were not considered. Fallen Jarrah husks degrade more quickly than do Marri husks, so the prevalence of Jarrah feeding may be underestimated. The study also could not identify the extent of feeding on insects and larvae and whether or not birds feed on the ground, in the canopy or both.

Distribution of major upper and middle-storey species

We determined if the major upper- and middle-storey species (Marri, Jarrah, Wandoo, Sheoak and Bull Banksia) were distributed evenly across the landscape elements of lowland, lower-slope, upper-slope and ridge-top using chi-squared goodness of fit tests. To avoid bias caused by over-sampling feed trees along the transects, only trees encountered in the fixed plots (*i.e.* at 200 m intervals) on each transect were included.

Distribution of Jarrah and Marri feed-trees

We used chi-squared contingency tables to test if the proportions of trees of these species actually used for feeding were associated with the species of tree and to determine if the trees of Jarrah and Marri actually fed on were distributed similarly across the four landscape elements. These analyses used data from both fixed and random plots and assumed that detection of feeding residues for the two species are similar. We do not distinguish feeding residues by black-cockatoo species for reasons of sample size and because our main objective was to identify landscape-scale patterns in the feeding activity of black-cockatoos in general.

Size and distribution of Jarrah and Marri

For each transect within each landscape element we also calculated the mean height and diameter at breast height (DBH) of the three largest Jarrah and three largest Marri trees within each plot and then used multivariate analysis of variance (MANOVA) to determine if the height and DBH of the largest Jarrah and Marri trees varied across the landscape. Prior to MANOVA, data were tested to ensure that they conformed to the assumptions of the test and any transformations required are indicated in the results.

Factors predicting the presence of feed trees

Lastly, we investigated possible predictors of whether or not a plot contained a feed tree using logistic regression, which tests the hypothesis that one or more independent variables (that may be continuous or categorical) predict the frequency of occurrence of a categorical dependent variable (see Floyd (2001) for a discussion of general principles with ecological applications). Variables measured in the 20m x 20m plots were considered as independent variables in logistic regressions as follows: (a) landscape position - three dummy variables equal to 1 if the plot is respectively on the lower slope, ridgetop or upper slope and 0 otherwise; (b) number of woody stems - the proportion of trees that were Jarrah, Marri, Wandoo, Banksia, and Sheoak; and (c) disturbance - dummy variables for the presence of cut stumps, fallen logs, fire scars, and logging tracks.

Results

Feeding residues and feed-tree plots

Jarrah and Marri feed trees were observed in 36 of 140 (25.7%) fixed-interval plots along transects. An additional 78 plots containing Jarrah and/or Marri feed trees were sampled where feed trees were encountered *ad hoc* along transects. Overall, including the 24 plots sampled for other purposes (see methods), we sampled 241 plots, of which 114 contained at least one feed-tree (*i.e.* feed-tree plots).

Most feed-tree plots contained Jarrah feed-trees (n = 26 of 36 fixed-interval feed-tree plots, 72.2%; n = 70 of 114 total feed-tree plots, 61.4%;), while less than half contained Marri feed-trees (n = 15 of 36 fixed-interval feed-tree plots, 41.7%; n = 52 of 114 feed-tree plots, 45.6%). Jarrah and Marri occurred in differing frequencies within fixed-interval plots, with Jarrah absent from 14.2% (n = 20 of 140 plots) and Marri absent from 35.7% (n = 50 of 140 plots) of fixed-interval plots. Thus, Jarrah feed-trees and Marri feed-trees occurred in 21.7% and 16.7% of fixed-interval plots in which these species were present, respectively.

We encountered 176 feed trees (Table 1), of which 54.0% (n = 95) were Jarrah and 46.0% (n = 81) were Marri. Most feed-tree plots contained only one feed-tree (n = 78 of 114 feed-tree plots, 68.4%), with similar proportions of plots containing a single Jarrah feed-tree (n = 51/70 plots, 72.9%) or a single Marri feed-tree (n = 39/52 plots, 75.0%). Eight (7.0%) feed-tree plots contained both a Marri and a Jarrah feed-tree. The number of feed trees per feed-tree plot ranged from 1 to 4 for Jarrah, and from 1 to 8 for Marri. Overall, the 241 total plots contained 1833 Jarrah stems and 622 Marri stems, a ratio of 2.95:1. The proportions of Jarrah and Marri stems that were feed trees were significantly different (Jarrah: 95/1833, 5.2% and Marri: 81/622, 13.0%; = 34.84, p < 0.001).

Most Marri feed-trees had feeding residues with the 'bottom-slice' markings indicative of feeding by FRTBC (n = 54 of 81 feed-trees, 66.7%), while about a third had residues with the 'levering' markings indicative of feeding by Baudin's Black-Cockatoos (n = 26 of 81 feed-trees, 66.7%). Six trees had residues with both 'bottom-slice' and 'levering' markings (n = 6 of 81 feed-trees, 7.4%). Markings were not recorded for 3 trees (n = 3 of 81 feed-trees, 3.7%). Similar proportions of Jarrah and Marri feed trees were classified as having 'old' feeding residues (Jarrah: n = 6 of 95 feed trees, 6.3%; Marri: n = 6 of 81 feed trees, 7.4%).

Distribution of major upper and middle-storey species

Significant chi-squared goodness of fit statistics based

Table 1

Number of feed trees across landscape positions, based on data from fixed plots only (n = 59 feed trees) and all plots n = 176 feed trees total).

	Ridgetop		Upper slope		Lower slope		Lowland		Total	
	Fixed	*All*	*Fixed*	*All*	*Fixed*	*All*	*Fixed*	*All*	*Fixed*	*All*
Jarrah	10	18	7	23	16	38	7	16	40	95
Marri	2	4	0	4	7	27	10	46	19	81

Table 2

The total number of woody stems >6m tall for each of the major tree species found in 20m x 20m plots at four different landscape locations. It is based on fixed-interval plots only (*n* = 140 fixed plots, *n* = 35 per landscape position), *i.e.* it excludes the extra plots located where feed trees were encountered along transects. Chi-squared values for each species are tests for equal distributions of trees across the four landscape categories. All chi-squared values are significant (p < 0.001).

| Species | Location | | | | |
	Ridgetop	Upper slope	Lower slope	Lowland	Chi-squared
Jarrah	326	288	440	81	237.3
Marri	142	83	93	39	60.1
Wandoo	6	0	2	309	888.3
Bull Banksia	95	119	73	10	88.4
Sheoak	128	159	50	0	187.2

on plants scored in the fixed plots indicated that each of the five main upper- and middle-storey species was not distributed evenly across the landscape (Table 2). Jarrah was most abundant on lower slopes and least abundant in lowland. Marri was most abundant on ridgetops and also least abundant in lowland. Wandoo occurred almost exclusively in lowland. Bull Banksia and Sheoak occurred mostly on upper slopes and ridgetops, followed by lower slopes. They were scarce in lowland. The ratio of Jarrah to Marri stems increased across landscape position: ridgetop (2.3:1), upper slope (3.5:1), and lower slope (4.7:1). Within lowland areas, Wandoo, Jarrah, and Marri occurred at a ratio of 7.9:2.1:1.

Distribution of Jarrah and Marri feed-trees

Based on data from all plots, Jarrah and Marri trees used for feeding were not distributed similarly across the landscape ($\chi_3^2 = 37.8$, p < 0.001) (Table 1). The result is also significant if only fixed plots are considered ($\chi_3^2 = 10.2$, p = 0.02). Jarrah feed trees occurred predominantly on the ridgetops and lower slopes, whereas Marri feed trees were mainly on the lower slopes and in the lowlands. With lowland fixed-interval plots, a quarter of Marri stems were feed trees (*n* = 10 of 39 stems in fixed-interval plots, 25.6%) (Tables 1 and 2).

Size and distribution of Jarrah and Marri

Multivariate analysis of the DBH and heights of Jarrah feed trees (Wilks' lambda $_{(6,180)}$ = 0.95, p = 0.62) and Marri feed trees (Wilks' lambda $_{(6,150)}$ = 0.92, p = 0.43) found no significant differences in feed tree size in relation to landscape position. The situation was different, though, when the three largest trees of each species in each plot were assessed in relation to landscape position. Jarrah trees differed significantly in size across the landscape (Wilks' lambda $_{(6, 678)}$ = 0.91, p < 0.001) in height ($F_{(3, 340)}$ = 10.2, p < 0.001) but not DBH ($F_{(3, 340)}$ = 1.5, p = 0.22). Jarrah trees were taller on the upper and lower slopes and shortest in lowland plots (Table 3). The three largest Marri trees/plot also differed significantly in size across the landscape (Wilks' lambda $_{(6, 386)}$ = 0.86, p < 0.001) in height ($F_{(3, 194)}$ = 4.1, p = 0.007) and DBH ($F_{(3, 194)}$ = 6.5, p < 0.001). Marri were largest in the lowlands and on lower slopes (Table 3).

Factors predicting the presence of feed trees

Multiple logistic regression with all independent variables identified only landscape position (p < 0.001) and the proportion of trees that are Wandoo (p = 0.021) as significant predictors of feed trees. Backward elimination where insignificant variables were successively removed confirmed a final model with only these variables and this model is summarized in Table 4. Below we interpret these results, bearing in mind that the proportion of Wandoo is zero for all landscapes other than lowlands. The short duration of the study precluded any analyses of temporal patterns.

In Table 4, the first row reports the significance of landscape overall (p < 0.001) while the following three rows report the results for the three dummy variables for lower slope, ridgetop and upper slope. These results show that, compared to lowlands with no Wandoo, the log-odds of a feed tree are 1.2, 2.3 and 2.2 lower for the lower slope, ridgetop and upper slope respectively. Hence feed trees are most common in lowlands without Wandoo, less common on the lower slopes and least common on the ridgetops and upper slopes. For lowlands with Wandoo, the log odds decrease by 0.4 for each increase of 10% in the proportion of trees that are Wandoo. Hence the evidence suggests feed trees are more common in lowlands, but only when Wandoo is absent. When the proportion of Wandoo trees in the lowlands is

Table 3

The height and diameter-at-breast-height (dbh) across landscape positions of: (a) the three largest Jarrah and Marri trees (determined by dbh) from fixed-interval plots in different landscape elements and (b) all Jarrah and Marri feed trees encountered. Key: L = lowland, LS = lower slope, US = upper slope, R = ridge.

| Position | Species | (a) 3 Largest Trees per Plot | | | (b) Feed Trees | | |
		n	dbh ± se (cm)	height ± se (m)	n	dbh ± se (cm)	height ± se (m)
L	Jarrah	45	41.1 ± 4.2	15.1 ± 0.8	16	64.3 ± 10.3	20.7 ± 1.0
LS		102	48.4 ± 2.0	18.8 ± 0.4	38	53.1 ± 3.7	18.6 ± 0.7
US		99	47.6 ± 1.8	18.7 ± 0.3	23	61.5 ± 4.7	20.3 ± 0.8
R		98	45.3 ± 2.1	17.5 ± 0.4	18	60.3 ± 6.2	19.6 ± 0.9
L	Marri	31	43.2 ± 4.8	15.0 ± 1.4	46	54.8 ± 4.4	18.6 ± 1.0
LS		48	33.3 ± 2.7	15.6 ± 0.9	27	50.5 ± 4.4	19.0 ± 1.2
US		54	26.4 ± 2.1	12.3 ± 0.6	4	38.8 ± 6.3	18.0 ± 1.8
R		67	26.9 ± 1.4	12.9 ± 0.5	4	32.1 ± 5.5	16.1 ± 3.8

Table 4

Summary of multiple logistic regression predicting log-odds (Exp(B)) of feed tree presence.

	B	S.E.	Wald	df	Sig.	Exp(B)
Landscape			22.381	3.0	0.000	
Lower Slope	-1.245	0.574	4.694	1.0	0.030	0.288
Ridgetop	-2.335	0.595	15.394	1.0	0.000	0.097
Upper Slope	-2.219	0.586	14.321	1.0	0.000	0.109
Wandoo	-4.147	1.062	15.258	1.0	0.000	0.016
Constant	1.755	0.519	11.412	1.0	0.001	5.781

about 50%, feed trees are about as common as they are on ridgetops and upper slopes. When more Wandoo trees are present in the lowlands, feed trees are less common there than they are on the ridgetops and upper slopes. The likelihood of feed trees on the lower slopes is higher than their likelihood in the lowlands if the proportion of Wandoo in the lowland is higher than about 30%. These results describe the current data set and some temporal variation may occur from year to year.

Discussion

Forest management in southwestern Western Australia is often focused on the retention of tree hollows for hollow-dependent fauna (*e.g.* Calver & Dell 1998, Abbott & Whitford 2002, Whitford & Williams 2002, Whitford & Stoneman 2004). While this is a vital element, it is important for management strategies to consider the full range of resources required by threatened fauna (Recher 2004). Black-cockatoos have high energetic requirements and a K-selected life history strategy, suggesting the importance of food availability for reproductive success and juvenile survivorship (Saunders 1977; Johnstone & Kirkby 1999, 2008; Cooper *et al*. 2002; Cameron 2005). This study indicates that landscape position is associated with the distribution of eucalypt feed trees for black-cockatoos, and that this association is particularly strong for Marri, with Marri feed trees concentrated on the lower slopes and in lowland areas at the study area.

Multiple logistic regression indicated that only landscape position and the proportion of trees that were Wandoo were significant predictors of where feed trees occurred, likely reflecting the tendency of Wandoo to displace competing eucalypts when present (Havel 1975a) and the predominance of Marri feed trees in lower slope and lowland plots. These findings suggest that black-cockatoos decide where to forage based upon landscape position and whether the vegetation type is a Jarrah-Marri admixture or Wandoo-dominated, and that these factors are the most robust landscape-level predictors for evaluating where high quality black-cockatoo feeding habitat is likely to occur.

This study also suggests that, at a landscape-scale, Marri may be a more important food resource for black-cockatoos than is Jarrah. While Jarrah and Marri occurred at a frequency ratio of near 3:1 within the study area, we encountered similar numbers of Jarrah (*n* = 95) and Marri feed trees (*n* = 81). In addition, a significantly higher proportion of Marri trees (13.0%) were used as feed trees than were Jarrah trees (5.2%). If further research demonstrates that this trend is robust in the face of possible annual variation, the case for a high conservation value for Marri will be strengthened.

Two factors support this conclusion about the high conservation value of Marri for black-cockatoos in the Jarrah forest. Firstly, Marri occurs at much lower abundances than Jarrah in the Jarrah forest. Whitford (2002) reports the frequency ratio of Jarrah to Marri as approximately 2:1 through the Jarrah forest, and Abbott (1998) cites unpublished forest inventory data indicating that Marri accounts for between 16% of stand basal area in the northern Jarrah forest and 33% in the southern Jarrah forest. However, the ratio of Jarrah to Marri may be as high as 9:1 in cutover forest areas (Abbott & Loneragan 1986). In this study, Jarrah stems outnumbered Marri stems by at least 2:1 in all landscape positions except for lowlands. Secondly, Marri is the primary food source for Baudin's Cockatoos, is often the principal food source for FRTBC, and is sometimes a major food for Carnaby's Cockatoo (Johnstone & Storr 1998; Saunders 1980; Abbott 1998; Johnstone & Kirkby 1999, 2008; Cale 2003; Cooper *et al*. 2003; Chapman 2007a). The value of Marri as a food source may relate in part to its energetic value, *e.g.* marri fruits are much richer in energy (7.32 kJ nut^{-1}) than are Jarrah fruits (1.24 kJ nut^{-1}) (although handling time for Marri fruits is longer) (Cooper *et al*. 2002).

No other variables considered in this study were significant predictors for black-cockatoo feed-trees. The lack of association with Marri stem densities likely relates to an increase in the productivity of Marri lower in the landscape, as suggested by the increase in DBH and tree height from ridge-tops to lowland areas. We suggest that the lack of significance for any of the disturbance variables probably reflects that these variables are indirect measures of historic (>20 years previous) logging practices, as well as the general homogeneity of stand structures within the study area. Further research is needed to address the relative habitat value of lightly-logged areas versus intensively logged areas.

While needing confirmation through broader study, the findings suggest the potential conservation value of efforts to conserve or restore lowland areas containing Marri within areas used for timber and mineral production. Bauxite mining removes laterite mantles along ridges and upper-slopes, so effects on black-cockatoo feeding habitat can be mitigated by minimising disturbance to low-lying areas where Marri feed trees are concentrated. Jarrah and Sheoak along ridgelines and mid-to-upper-slopes will be lost, but conserving large Marri may be more important in terms of reducing impacts on food availability. Historically, forestry operations have selectively removed large Marri trees for timber wood-chipping, as well as senescent trees for safety and to facilitate Jarrah growth and regeneration (Heberle 1997, Wardell-Johnson *et al*. 2004). Management prescriptions in the Forest Management Plan 2004–2013 increased the amount of Marri trees retained to provide hollows for arboreal fauna (Conservation Commission 2004). These prescriptions could be adjusted to include provisions for the retention of potential Marri feed trees and, where practical, the establishment of stand structures that facilitate the growth of larger canopy volumes. These considerations relate to Marri feed trees and we note the need for information on the landscape

distribution of black-cockatoo nest sites in order to ensure that both feeding and breeding habitat are retained.

Further research is needed in three areas. Firstly, little is known about regional variation in the distribution of eucalypt food sources for black-cockatoos. This is particularly true for the Karri *Eucalyptus diversicolor* forest, where there are no published studies on the incidence of black-cockatoo food resources and few data on the abundance and distribution of Marri. The Karri forest is the main breeding area for Baudin's Cockatoo and the availability of Marri is likely to be important for breeding success (Johnstone & Kirkby 2008). Secondly, this study focused on landscape-scale patterns in feed-tree distribution, and it remains unclear what factors influence individual feed tree selection. Studies in eastern Australia, for example, indicate that cockatoos may prefer larger trees because they provide greater protection from predators while feeding on inner branches and also reduce the number of movements required while foraging (Pepper *et al*. 2000; Maron & Lill 2004; Chapman & Paton 2005, 2006; Cameron & Cunningham 2006). Differences in fruit characteristics and productivity could also affect feed tree selection. However, while Cooper *et al*. (2003) found that FRTBC prefer Marri fruits with larger numbers of seeds and seeds of high individual weight, Weerheim (2008) found no differences in fruit morphology or seed nutrient content between Marri trees selected for feeding and trees not fed upon. Both studies did, however, observe that FRTBC return to certain trees preferentially. Phenological patterns for Marri have not been well-documented (Paap 2006), and thus it is not clear how the selection of individual trees for feeding may change over time, *e.g.* whether a tree may be fed on in years in which it fruits strongly but not in those years when it does not, and how phenology influences landscape-scale food availability. Thirdly, this study was restricted to a single year and hence did not document whether the trends described are robust within annual variation. For example, Wandoo flowers and nectar are an important food for Carnaby's Cockatoos in some years at some sites (Ron Johnstone, Western Australian Museum, unpublished data). Thus follow-up monitoring is advisable to confirm the conservation value of Marri for black cockatoos in the Jarrah forest. This monitoring would benefit from the extended observation of flocks in order to better document the use of food sources leaving feeding residues that are ephemeral or difficult to identify.

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