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# The anatomy of a failed offset

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## Abstract

Biodiversity offsetting is widely applied but its effectiveness is rarely assessed. We evaluated the effectiveness of a nest box program intended to offset clearing of hollow-bearing trees associated with a freeway the upgrade in southern Australia. The offset targeted three threatened vertebrates: squirrel glider (*Petaurus norfolcensis*), brown treecreeper (*Climacteris picumnus*) and superb parrot (*Polytelis swainsonii*). Clearing led to the loss of 587 tree hollows and the offset was the placement of an equivalent number of nest boxes in nearby woodland (1:1 ratio). Of these, we monitored 324 nest boxes in six sample periods between 2010 and 2013, yielding 2485 individual checks of nest boxes.

For the three target species, we found: **(1)** no records of nest box use by the superb parrot, **(2)** two records of the Brown Treecreeper (0-0.76% of accessible nest boxes used per survey period), and **(3)** seven records of use of nest boxes by the Squirrel Glider (0-2.1% of accessible nest boxes used per survey period). Rates of nest box use by the Superb Parrot and Squirrel Glider were markedly lower than rates of use of hollow-bearing trees observed in other investigations. Low levels of use by target species coupled with the extent of nest box attrition suggest the offset program will not have counterbalanced the loss of the hollow-bearing trees.

We make suggestions for improving future offset programs including a greater emphasis on: (1) avoiding impacts on hollow-bearing trees; **(2)** offset effectiveness as a measure of compliance; and **(3)** using realistic offset ratios.

**Keywords**: Nest boxes; cavity-dependent species; south-eastern Australia; tree hollows; vegetation clearing; endangered box gum grassy woodland.

## 1. Introduction

Biodiversity offsetting is a widely used approach that attempts to mitigate the impacts of human activities on biodiversity (Maron et al. 2016). It involves generating conservation benefits in one area that aim to compensate for the impacts of a given form of development in another area. However, the large and rapidly increasing literature on offsets is highlighting potential problems with offsetting, such as the relatively narrow range of impacts on biodiversity that can be offset (e.g. Gibbons and Lindenmayer 2007; Maron et al. 2015b; Gibbons et al. 2016; Maron et al. 2016).

One major deficiency in much of the work on offsets is that their effectiveness is rarely subject to empirical assessment after implementation (Tischew et al. 2010; Bull et al. 2013) (but see Pickett et al. 2013)). The loss of some kinds of natural assets can be particularly difficult to offset and hence particularly important to evaluate post-hoc. An example is large old trees which can take a long time to develop and which have a range of key characteristics not found in small young trees, small old trees or large young trees (Lindenmayer and Laurance 2016). Cavities or hollows are a critical characteristic of large old trees and they are an important nesting and denning resource for a wide range of species in many ecosystems globally (Fischer and McClelland 1983; Remm and Lohmus 2011). Populations of large old trees with hollows are declining in a wide range of forest, savanna, agricultural and urban environments around the world, often as a result of logging, land clearing or other destructive activities (Lindenmayer and Laurance 2016). Offsetting is sometimes used in an attempt to mitigate the effects of the loss of large old trees with hollows, particularly through the establishment of nest boxes to replace the cavity provision role of these trees. However, empirical assessments of the efficacy of such offsets programs are lacking, particularly at large spatial scales.

Here we address this knowledge gap through a four-year case study of an offset in southern New South Wales, south-eastern Australia which entailed the establishment of nest boxes to compensate for losses of natural hollows due to the widening of Australia's most heavily used interstate freeway, the Hume Highway. The Hume Highway links the nation's two largest cities (Sydney and Melbourne) and its expansion had multiple ecological impacts. These included removal of habitat for hollow-dependent threatened species listed at the State and National level, clearing of nationally endangered temperate box gum grassy woodland, and removal of hollow-bearing trees (Australian Government Department of the Environment, Water, Heritage and the Arts, 2010; NSW Government Department of Planning, 2010). Thousands of trees were cleared as part of the road widening, realignment and construction, including many large old trees that play a range of key ecological roles within box gum grassy woodland. One of the most important roles of large old trees is the provision of nesting and denning habitat for an array of cavity-dependent native vertebrates (Manning et al. 2006; Lindenmayer et al. 2016b). Indeed, the loss of hollow bearing trees is listed as a key threatening process under the New South Wales *Threatened Species Conservation Act (1999)* (NSW Office of Environment and Heritage 2007). In addition to the impacts of establishing human infrastructure, populations of large old trees in box gum grassy woodland are threatened by a range of other processes including (among others): livestock grazing (Fischer et al. 2009), secondary salinity (Stirzaker et al. 2002), firewood collection (Driscoll et al. 2000), and fire (Crane et al. 2016).

The establishment of nest boxes was one component of a broader biodiversity offset strategy implemented to satisfy legislative requirements under State and National environmental protection laws (Roads and Traffic Authority, 2010). Here, we focus on the nest box component of the offset strategy which was designed to compensate for the loss of tree hollows (Department of Environment and Climate Change Undated) (Department of

Planning 2010). The loss of tree hollows was compensated at a ratio of 1:1, resulting in the establishment of 587 nest boxes. Criteria for the design and installation of nest boxes emphasized the need to establish a diversity of nest box types characterized by different entrance sizes and internal volumes, and the need to monitor patterns of nest box use and occupancy (Department of Environment and Climate Change Undated).

Evaluating the effectiveness of an offset requires an understanding of the baseline or counterfactual scenario against which the outcomes delivered by the offset are judged (Maron et al. 2015b). According to State policy at the time of this development, biodiversity offsets implemented in New South Wales "should aim to result in a net improvement in biodiversity over time", and "enhancement of biodiversity in offset areas should be equal to or greater than the loss in biodiversity from the impact site" (Department of Environment and Climate Change 2008). This implies that the baseline is the biodiversity value at the impact site before clearing, although in practice, offsetting in New South Wales assumes a decline of 10% on average over an unspecified time horizon (Maron et al. 2015a). The criteria used to guide the installation of the nest boxes (Department of Environment and Climate Change Undated) http://www.environment.nsw.gov.au/biodivoffsets/oehoffsetprincip.htm) states that:

*To ensure success, nest-boxes must provide suitable habitat until such time that retained trees close to the alignment develop nest hollows and cavities to replace those that were lost.*

From an ecological perspective, this means that the nest boxes must be effective for between 50 and 100 years after installation or until significant new nest hollows develop (Lindenmayer et al. 2009), and presumably provide "suitable habitat" equivalent to the amount and quality of habitat provided by tree hollows prior to clearing. However, research on nest boxes elsewhere in our study region suggest that occupancy of nest boxes by species of conservation concern is generally low (Lindenmayer et al. 2015).

A key part of the offset policy underpinning this project was to establish nest boxes for three threatened taxa known to occur in box gum grassy woodland adjacent to where large old scattered trees were being cleared (Department of Environment and Climate Change 2008). These were two birds: the brown treecreeper (*Climacteris picumnus)* and superb parrot (*Polytelis swainsonii*), and the nocturnal marsupial, the squirrel glider (*Petaurus norfolcensis*). Design criteria for these nest boxes were specified in various New South Wales Government documents including Overton et al. (2013) and Department of Environment and Climate Change (2008).

Our first question in this investigation was: **Are nest boxes an effective offset for clearing of hollow-bearing trees for the three species of conservation concern?** There were two components to this evaluation: are the nest boxes used by the target species at rates similar to those expected by the lost tree hollows? And is it likely that the next boxes will remain suitable for the duration that the lost tree hollows would have done? Although pre-clearing surveys of the impacted habitat were conducted (Abigroup 2010), these data were not made available to us, and hence the occupancy of the lost tree hollows by the three species of conservation concern (as well as other cavity-dependent fauna) at the impact sites could not be known. To estimate the counterfactual (occupancy of natural tree hollows by the species of conservation concern in the absence of tree clearing), we drew upon data from a range of sources (see Section 2: Methods). At the outset of this investigation, we were doubtful of the efficacy of the establishment of nest boxes as an effective offset. This was because research on nest boxes elsewhere in our study region indicated a paucity of use by species of conservation concern (Lindenmayer et al. 2015).

As part of conducting surveys of the nest boxes for the three species of conservation concern, we also gathered data on nest box use by other cavity-dependent taxa. This enabled us to address a second question: **What are the overall levels of nest box use and by which**

**species?** In answering this question and using data on covariate measures of nest boxes and site-level characteristics, we also sought to quantify the factors influencing nest box use by different species of cavity-dependent fauna.

## 2. Methods

### 2.1 Study area and kinds of nest boxes installed

Our study area was temperate eucalypt box gum grassy woodland adjacent to the Hume Highway between the towns of Coolac and Holbrook in southern New South Wales. Areas of remnant native woodland and scattered hollow-bearing trees were cleared to accommodate the widening of the Hume Highway. The cleared trees were estimated to support 587 hollows and the corresponding offset was the establishment of 587 nest boxes. These were of varying dimensions to offset the loss of a range of types of hollows, although the offset did not attempt to compensate for the other habitat values of the trees that were cleared. Of the 587 nest boxes, 263 could not be monitored for occupational health and safety reasons such as being installed very close to the Hume Highway. We monitored the remaining 324 nest boxes between 2010 and 2013 and of these, 83 were designed specifically for squirrel glider, 77 for the brown treecreeper, and 37 for the superb parrot (see Appendix A for design details of each box type). Other kinds of nest boxes monitored were those for bats (62 boxes), the common brushtail possum *Trichosurus vulpecula* (42 boxes), the common ringtail possum *Pseudocheirus peregrinus* (13 boxes) and large birds (10 boxes).

We inspected nest boxes in the spring of 2010, 2011, 2012 and 2013 and summer of 2011 and 2012, yielding 2485 individual checks of nest boxes over the four-year duration of the study. During each survey, we recorded both animal presence and other signs of use such as scats, hair, feathers and nests. Where there was uncertainty in identifying species from the evidence of nest box use, we sent samples of scats and hair to an expert for formal identification. In addition to identifying which species used the nest boxes, we also recorded whether nest boxes were functional (e.g. if they had fallen to the ground) and were therefore capable of being occupied or indeed in some cases whether the box was still present at all.

## 2.2 Baseline data for the counterfactual scenario and the evaluation of offset effectiveness

The counterfactual scenario for assessing the effectiveness of nest boxes as an offset demanded quantifying the occupancy of natural tree hollows by the three target species of conservation concern in the absence of tree clearing. The absence of pre-clearing survey data from the impacted sites meant that occupancy rates for the brown treecreeper, squirrel glider and superb parrot prior to the clearing of hollow-bearing trees and the establishment of the offset was not known. We therefore estimated the counterfactual scenario by drawing on data from a range of other sources. Our first dataset for estimating the counterfactual scenario was derived from a matched case-control study of nest trees occupied by the superb parrot in box gum grassy woodland (Crane et al. 2010), including the areas where this investigation was located (Manning 2004; Manning et al. 2013). That study identified 136 occupied nest trees from a sample population of 2857 large old hollow-bearing trees located in 513 50 x 20m plots. These data equate to 4.7% occupancy of trees with natural cavities by the superb parrot during the breeding season for the species.

Our second dataset for analyzing the counterfactual scenario was a radio-tracking study of den use by the squirrel glider within box gum grassy woodland in the broader study area (Crane et al. 2008; Crane et al. 2010; Crane et al. 2012). That study showed that individuals may use between 2-13 hollow-bearing trees as den and nest sites and swap regularly between these trees from day to day (Crane et al. 2010). The average denning range of the species in our study region (i.e. the area encompassed by the suite of nest trees used by an individual) is 3.6 ha (Crane et al. 2010). Approximately one in every ten of the old, large diameter hollow-bearing trees within a denning range was occupied by the species in a year, although most individuals have a primary and secondary den site used most frequently with other trees used less often (M. Crane, Lindenmayer and Cunningham unpublished data).

To the best of our knowledge, there have been no investigations specifically targeting the rates of occupancy of natural cavities in trees by the brown treecreeper in our study region. Other studies have indicated that the brown treecreeper uses a variety of kinds of hollows for nesting, but primarily exploits dead branches, spouts, tree trunks and fallen logs (Higgins et al. 2001). The species is also known to use nest boxes (Higgins et al. 2001).

For nest boxes to be effective, the species targeted by such programs need to occur in the surrounding landscape so that animals can occupy them. Examinations of threatened species profiles developed by the New South Wales Office of Environment and Heritage (2017) confirmed that the offset sites occurred within the known ranges of all three species targeted in this study. This corroborated data from our field surveys of the three target species in the region based on spotlighting for arboreal marsupials and point interval counts for birds completed in 2011 and 2013 at 68 long-term field sites within 10 km of where nest boxes had been established (see Lindenmayer et al. 2016a; Lindenmayer et al. 2016c).

### 2.3 Estimated costs of the nest box offset program

We compiled information from the New South Wales Roads and Maritime Services on the range of costs (in 2010 Australian dollars) associated with the establishment of the nest box offset program. These included pre-establishment strategic planning, nest box construction, and post-establishment monitoring.

## 3. Data exploration and analyses

### 3.1 Comparison with the counterfactual scenario

To answer our first question (**<u>Are nest boxes an effective offset for clearing of hollow-bearing trees for the three species of conservation concern</u>?**), we compared rates of use of nest boxes attached to trees by each of the species of conservation concern with the rates of occupancy of natural hollows in trees from studies outside the areas subject to clearing for highway upgrading (superb parrot and squirrel glider). Equivalent data for the brown treecreeper were unavailable. For these comparisons, we included only boxes with an entrance large enough to permit entry for a given species. Data on the 62 bat boxes (that have a small entrance) were removed for all three target species of conservation concern. For the squirrel glider and the superb parrot, we also removed data on the 77 nest boxes designed for the brown treecreeper.

### 3.2 Overall patterns of use

To answer our second question **(What are the overall levels of nest box use and by which species?**), we employed Bayesian binary logistic regression modelling to analyse factors influencing nest box use by the following two groups of animals. These groups were: **(1)** mammals (black rat, brush-tailed phascogale, common brushtail possum, common ringtail possum, Gould's wattled bat, house mouse, sugar glider, squirrel glider, yellow-footed antechinus, and unknown glider, unknown possum); and **(2)** birds (brown treecreeper, common starling, crimson rosella, eastern rosella, grey shrike-thrush, white-throated treecreeper, unknown bird and unknown rosella). We also modelled the five individual species with sufficient presence data to facilitate further analysis (black rat, common brushtail possum, common ringtail possum, yellow-footed antechinus and feral honeybees).

To quantify the factors influencing nest box use, we modelled the effects of the following covariates: survey occasion (spring 2010, spring 2011, summer 2011, spring 2012, summer 2012 and spring 2013); number of paddock trees within 500 metres; nest box type (brown treecreeper, squirrel glider, superb parrot, bat, common brushtail possum, common ringtail possum and large bird); the diameter of the tree to which a nest box was attached; dieback score for the tree to which a nest box was attached; and distance to closest major patch of native woodland vegetation. In addition, for an area of 1 ha around each nest box, we measured or calculated values for: the total number of stems in the surrounding vegetation; number of trees greater than 50cm in height; number of hollow bearing trees greater than 50m; topographic wetness index (TWI); and lithology fertility rating.

The response variable for all analyses was the presence/absence of the species or species group of interest which we modelled using a Bayesian logistic regression with a random effect for site. We chose uninformative but proper priors for the fixed effects components and minimally informative but proper priors for the variance components of our models. Specifically, we used Student t-distributions for the regression parameters to minimize the effects of complete separation. We used a default prior for the random effect standard deviation (site). We summarized the logistic regression model parameters by the posterior mean and 95% credible intervals. We conducted the analysis using the brms package (Buerkner 2015) in R version 3.2.1 (R Core Team 2015) using the RStudio interface (RStudio Team 2015).

## 4. Results

### 4.1 Are nest boxes an effective offset for clearing of hollow-bearing trees for species of conservation concern?

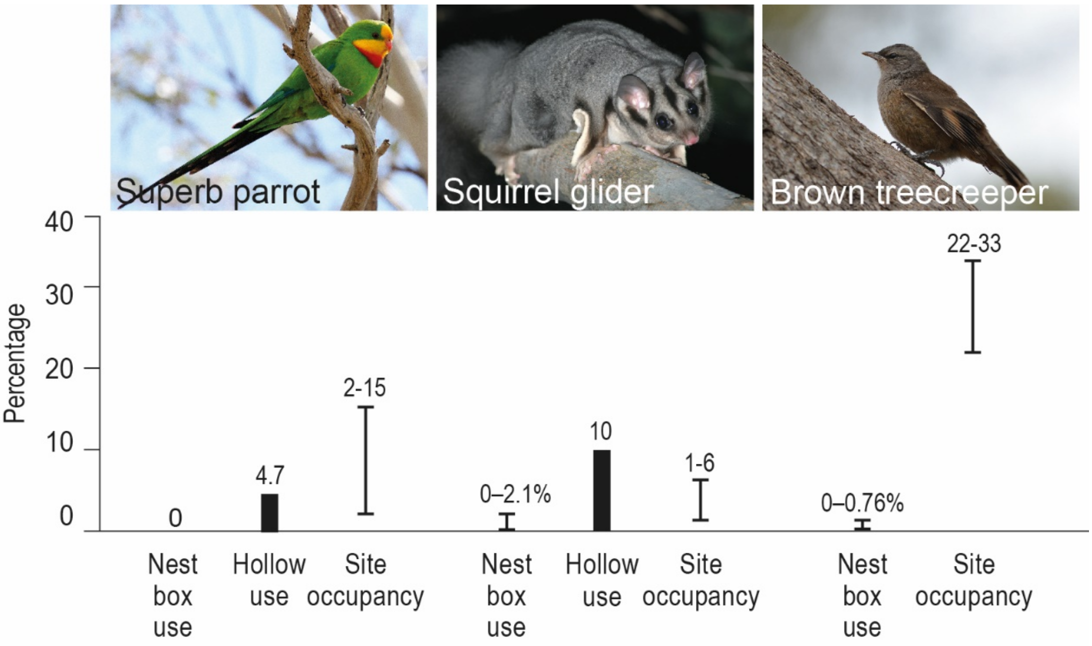
We found limited or no use of nest boxes by the three species of conservation concern targeted by the offsets program, including in the boxes specifically established for them. We recorded no cases of nest box use by the superb parrot, including boxes specifically designed for the species (Table 1). This contrasts with the values from the studies by (Manning 2004; Manning et al. 2013) showing that 4.7% of hollow-bearing trees were used as nest sites by the superb parrot (Fig. 1). That is, our results suggested that nest boxes are not a suitable method for offsetting the loss of nest sites for this species. The superb parrot was detected at 2% of sites surveyed in 2011 and 13% of sites in 2013 that were located near the offset impact areas.

Of all 324 nest boxes observed in this study, seven were used by the squirrel glider across the four-year duration of our study, with the percentage use of nest boxes ranging from zero to 0.6% of nest boxes per survey period (Table 1). Of the 185 nest boxes considered accessible to the squirrel glider, percentage use values ranged from 0% to 2.1% per survey period. Only one of the seven records of nest box use by the squirrel glider was in a box specifically designed for the species. Rates of nest box use were lower than those recorded for old, large diameter hollow-bearing trees within the denning range of a given individual in a comparable survey period (approximately 10%) (Crane et al. 2010) (Crane et al., Lindenmayer and Cunningham unpublished data). Other things being equal, to offset the loss of nesting sites for this species, at least five trees with suitable nest boxes are required for every one hollow-bearing tree destroyed. The proportion of long-term sites near the offset impact areas in which the squirrel glider was detected ranged from 1% in 2011 to 6% in 2013 (Fig. 1).

We recorded the brown treecreeper using two nest boxes in one survey period (0.6% of nest boxes in spring 2010; see Table 1). Neither of the two records of the brown treecreeper were from a box designed for the species. After removing nest boxes inaccessible to the brown treecreeper, percentage use values ranged from 0% to 0.76% per survey period. The brown treecreeper was present at 22 and 33% of long-term sites that we surveyed in 2011 and 2013, respectively (Fig. 1).

**Fig. 1.** Percentage rates of nest box use by each of the species of conservation concern (denoted nest box use), rates of use of large old hollow-bearing trees from studies outside the areas subject to clearing for highway upgrading (for superb parrot and squirrel glider only) (denoted hollow use), and the proportion of long-term sites where each of the three target

species had been recorded between 2010 and 2013 (denoted site occupancy). Data on nest box use excludes boxes with an entrance too small to permit entry of a given species.



## 4.2 What are the overall levels of use of the nest boxes and by which species?

Over the four-year duration of our study and for a given survey period, between 44.7% and 65.1% of nest boxes contained an animal or showed signs of use (Table 1). We recorded 17 species occupying the 324 nest boxes, of which four were exotic species: the feral honeybee, black rat, house mouse and common starling. The most commonly recorded species were the yellow-footed antechinus, with usage rates varying between survey periods from 12.0-13.7%, the common brushtail possum (11.0-11.4%), feral honeybee (7.0-11.4%), black rat (4.2-13.5%), common ringtail possum ( (2.6%-5.7%), and common starling (0.6-2.5%) (Table 1).

**Table 1:** Percentage of nest boxes where evidence of use was recorded over four years of monitoring. Exotic species are marked with an asterisk*.

| **Common name** | **Scientific name** | **2010** | **2011** | | **2012** | | **2013** |
|---|---|---|---|---|---|---|---|
| | | **Spring** | **Spring** | **Summer** | **Spring** | **Summer** | **Spring** |
| Black rat* | *Rattus rattus* | 4.2 | 13.6 | 4.3 | 7.8 | 10.8 | 5.1 |
| Brown treecreeper | *Climacteris picumnus* | 0.6 | 0 | 0 | 0 | 0 | 0 |
| Brush-tailed phascogale | *Phascogale tapoatafa* | 0.3 | 0 | 0.6 | 0.3 | 0.3 | 0.7 |
| Common brushtail possum | *Trichosurus vulpecula* | 11.5 | 11.4 | 11.4 | 13.1 | 10.5 | 11.1 |
| Common ringtail possum | *Pseudocheirus peregrinus* | 2.6 | 6.5 | 4.0 | 5.9 | 4.3 | 5.7 |
| Common starling* | *Sturnus vulgaris* | 0.6 | 2.5 | 1.9 | 0.7 | 1.6 | 1.4 |
| Crimson rosella | *Platycercus elegans* | 1.3 | 0.6 | 0.3 | 0 | 0 | 0.7 |
| Eastern rosella | *Platycercus eximius* | 0.3 | 0.3 | 0 | 0 | 0 | 0.3 |
| Feral honeybee* | *Apis mellifera* | 7.0 | 11.7 | 11.4 | 7.8 | 8.2 | 8.1 |
| Goanna | *Varanus varius* | 0.3 | 0 | 0 | 0.3 | 0 | 0 |
| Gould's wattled bat | *Chalinolobus gouldii* | 0.3 | 0.3 | 0.3 | 0 | 0.7 | 0 |
| Grey shrike-thrush | *Colluricincla harmonica* | 0 | 0.6 | 0.3 | 0 | 0 | 0 |
| House mouse* | *Mus musculus* | 0 | 1.5 | 0 | 0 | 0.9 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Marbled gecko | *Christinus marmoratus* | 0 | 0.6 | 0.3 | 0.3 | 0 | 0.3 |
| Peron's tree frog | *Litoria peronii* | 0 | 0 | 0.3 | 0.3 | 0.7 | 0 |
| Squirrel glider | *Petaurus norfolcensis* | 0.6 | 0.3 | 0 | 0.3 | 0.7 | 0.3 |
| Sugar glider | *Petaurus breviceps* | 0.9 | 0.3 | 0.6 | 0.9 | 0.3 | 0.3 |
| Unknown animal | Unknown Animal | 0 | 0 | 0 | 0.3 | 0 | 0 |
| Unknown bird | Unknown Bird | 0 | 0 | 0 | 2.3 | 0.7 | 0.3 |
| Unknown glider | Unknown Glider | 0 | 0.6 | 0.6 | 0.7 | 0.7 | 3.0 |
| Unknown possum | Unknown Possum | 0 | 0 | 0 | 1.3 | 0 | 0 |
| Unknown rosella | Unknown Rosella | 0 | 0 | 0 | 0.3 | 0.3 | 0 |
| White-throated treecreeper | *Cormobates leucophaea* | 0.3 | 2.2 | 0.6 | 1.6 | 0.3 | 0.7 |
| Yellow-footed antechinus | *Antechinus flavipes* | 13.7 | 12.0 | 13.3 | 13.1 | 13.1 | 12.5 |
| Any | Any | 44.7 | 65.1 | 50.3 | 57.4 | 54.1 | 50.5 |
| **Number of boxes surveyed** | | **313** | **324** | **324** | **305** | **305** | **297** |

### 4.3 What factors influenced nest box use?

We constructed Bayesian logistic regression models of the factors influencing the use of nest boxes by the five most commonly recorded species and for which there were sufficient data to facilitate statistical analyses (the yellow-footed antechinus, common brushtail possum, common ringtail possum, black rat and feral honeybee) (Appendix B). Nest box design was a significant factor in all of the final models with marked, inter-specific differences in the kinds of boxes used by different species (Appendix B). There was a positive effect of the diameter of the tree to which a nest box was attached in the model for the common ringtail possum but a negative effect for the black rat. The models for the yellow-footed antechinus and the feral honeybee contained evidence of a positive relationship between nest box use and the number of stems in the vegetation characterizing the surrounding landscape. There also was evidence of season and/or year differences in the proportion of nest boxes used by the common ringtail possum, black rat and feral honeybee.

Other significant covariates in the models we constructed included an effect of the underlying lithology and topographic wetness of the sites where nest boxes were established (Appendix B). The feral honeybee more often used nest boxes in locations where there was a high value for the topographic wetness index whereas the reverse effect characterized the model for the common ringtail possum (Appendix B).

### 4.4 Nest box attrition

Approximately 8.3% (27/324) of nest boxes became ineffective for use during the four years of our study. There were several reasons for nest box failure with the two most prominent being boxes falling from trees (14 boxes), and presumed theft (7 boxes).

### 4.5 Estimated costs of the nest box offset program

The development of a plan for subsequent nest box establishment cost AU$50,000. The cost of construction was AU$200 per nest box or a total of AU$64,800. The cost of installation was AU$262 per box or AU$84,888 in total. Monitoring of the 324 nest boxes was completed by The Australian National University under contract with the New South Wales Department of Roads and Maritime Services at a total cost of AU$64,000 or approximately AU$197.50 per box for each of six survey periods (or $33.90 per box per survey period). That is, the total cost of establishing and monitoring nest boxes under this offset program was AU$199,688.

## 5. Discussion

The use of offsets in conservation and environmental management is widespread globally (Gibbons et al. 2016; Maron et al. 2016) and is rapidly increasing (Ives and Bekessy 2015), but the effectiveness of such an approach has rarely been subject to empirical assessment, particularly after an offset has been implemented (Pickett et al. 2013; May et al. 2016). We addressed this knowledge gap in the study reported here on the use of nest boxes designed to offset the clearing of hollow bearing trees as part of the widening of a major highway in rural Australia. Our analyses revealed that the nest box strategy examined here was not sufficient to offset impacts of development on the availability of nesting sites for at least two of the target species of conservation concern (i.e. squirrel glider, superb parrot), but had greater utility as a method to offset the loss of nesting sites for common species. In the remainder of this paper we further discuss these sobering results. We conclude with suggestions for improving future offset programs.

### 5.1 Limited nest box use by target threatened species

The key finding from our empirical study was the relative paucity of records of use of nest boxes by target species of conservation concern (or complete absence in the case of the superb parrot) (Fig. 1). The low rates of use of trees with nest boxes relative to usage patterns of hollow-bearing trees in other investigations in nearby areas, coupled with the occurrence of the three species in the general area where nest boxes were established, has demonstrated that the offset for these animals has largely failed. Our results are similar to those of Le Roux et al. (2016) whose research in the same broad ecological community reported slightly higher overall occupancy rates, but zero occupancy by threatened species (including the superb parrot) and domination of nest boxes by common or exotic species. However, some of our results showing low levels of occupancy for species of conservation concern differ from those of other researchers who have found that nest boxes specifically designed for particular taxa can support populations of those species (Goldingay et al. 2015), including the squirrel glider that was targeted in our study. The reasons for the differences between studies remain unclear. A possible explanation for the differences between studies may have been associated with the quality of work undertaken by private contractors to install nest boxes. In particular, the boxes were often were poorly attached to small diameter trees (so that the mounting brackets and the box were unstable). This problem may have not only contributed to reduced levels of occupancy but also contributed to the attrition of more than 8% of the nest boxes over the duration of our study. An additional explanation may be that other studies such as that by Goldingay et al. (2015) were undertaken in areas where the abundance of hollow-bearing trees was limited and/or the population density of the species greater, and hence rates of nest box occupancy may be expected to be relatively high. The duration of our study was four years and it is possible that we may have achieved high rates of nest box occupancy over a more prolonged period. However, other longer-running studies (Lindenmayer et al., 2015; Crane et al., unpublished data), also have met with limited or no success for the species of conservation concern targeted in this study. Moreover, all of the target species occur within or very close to where the nest boxes were established. Both these factors suggest that a longer study may not have met with more success than we have reported here.

### 5.2 Overall patterns of nest box use and factors influencing use

We found that the most common species of vertebrates using the nest boxes were species that are relatively common in woodland landscapes (the yellow-footed antechinus, common brushtail possum and common ringtail possum) and/or were exotic species (the feral honeybee, black rat and common starling) (Table 1). Statistical models of the factors affecting nest box occupancy for the five most commonly recorded species (see Appendix B) typically included a combination of nest box characteristics, attributes of the site or landscape surrounding where the nest box was located, and environmental features of the location (such as topographic wetness index or underlying lithology). This underscores the importance of factors at multiple scales affecting the probability of nest box occupancy, ranging from those that corresponded to the individual nest box level, to site and landscape level features.

We found no evidence for a positive or negative effect on nest box occupancy of variables such as the number of large old paddock trees in the surrounding landscape nor the number of hollow-bearing trees within 50 metres of a nest box (Appendix B). There also was no evidence of significant effects of dieback of trees in the surrounding vegetation on nest box occupancy (Appendix B). The reasons for the lack of influence of these variables remain unclear. Paddock trees are often used for nesting and foraging by species such as the squirrel glider and superb parrot (Manning and Lindenmayer 2009; Crane et al. 2012) and at the outset of the project we anticipated this variable may be important for the species in models of nest box occupancy. It is possible that where such trees are prevalent, there is limited need for animals to find shelter in nest boxes.

We found that nest boxes were sometimes occupied by species such as the black rat and common starling (Table 1), which are significant vertebrate pests in Australian agricultural landscapes. This has implications for offset policies because of the risks of perverse outcomes such as the potential to create nesting resources for pest species, including those that might compete with target species of conservation concern.

### 5.3 The anatomy of a failed offset and some recommendations for improvement

Several factors influenced the outcomes of the offset examined in this study. Whilst the provision of nest boxes was well intentioned, we believe that future offset programs might be more effective if key recommendations, outlined below, are taken into account.

First, the 1:1 offset ratio used to compensate tree hollows with nest boxes was inadequate as it failed to account for the risk of offset failure (Maron et al. 2012; Miller et al. 2015; Gibbons et al. 2016). Although the time between impact and the installation of next boxes was minimized (Department of Environment and Climate Change Undated) the low usage rate of nest boxes we observed suggests a high offset ratio would be required to achieve no net loss using this strategy. In the case of the squirrel glider and based on comparable occupancy rates for natural cavities in hollow-bearing trees, multipliers of at least five trees with a suitable nest box will be required to offset every one tree hollow that is cleared. That is, there would need to be a substantially larger number of nest boxes installed than the number of hollow-bearing trees lost in a development project to provide a benefit that counterbalances the loss of nesting hollows. However, nest boxes may not replace such functions at all for some species like the superb parrot.

The relatively high rate of attrition of nest boxes may well mean that they are rendered non-functional relatively soon after they are installed and hence well before the cavity-provision role of large old trees (which experience a much lower rate of attrition than nest boxes [see (Crane et al. 2016)], can be offset. This was known prior to the establishment of the offset; the nest box criteria developed by the Department of Environment and Climate Change (undated) stated that nest boxes were likely to deteriorate after 5-10 years and needed to be checked twice yearly until cavities develop in trees in the surrounding vegetation (typically when trees are 80-120 or more years old). Given this, we strongly suggest that a key part of offset policy must be to conduct due diligence on the likely effectiveness of a given offset approach before it is undertaken. For example, this should include a detailed prior assessment of previous work on the use of nest boxes by particular target species, including they numbers and types of boxes that are occupied (if they are used at all) and hence an appraisal of the likelihood of success (or failure) of such an offset strategy.

Until an effective, timely, and lasting offset for tree hollows can be demonstrated as viable, we suggest that hollow-bearing trees should be treated as "red flag" attributes, particularly where they support nesting sites for threatened and uncommon species, and impacts avoided during developments. Where this is not feasible, we suggest that an offset policy should include: **(1)** combined natural regeneration and/or establishment plantings of restored woodland alongside guaranteed long-term nest box maintenance (i.e. repair or regular replacement over many decades) until new cohorts of hollow-bearing trees are recruited; **(2)** protection and management of areas containing mature trees that are under threat from ongoing land uses; and **(3)** a suitable multiplier that accounts for the comparative low rate of use of nest boxes relative to occupancy of hollow-bearing trees (see above), together with the long time lag between impact and offset delivery.

A substantial multiplier on the number of nest boxes required, coupled with a demand for long-term maintenance and regular replacement of nest boxes, means higher costs. Therefore, cost effectiveness analysis should be considered when comparing potential options for offsets. Indeed, the AU$199,688 expended on the largely unsuccessful nest box offset program examined here was manifestly inadequate given low levels of nest box use by target species and high rates of attrition of nest boxes. An approximation of the cost of making this offset effective is $12.16 million dollars (in 2010 Australian dollars). This was based on the cost of: **(1)** monitoring all boxes twice per year for 90 years; **(2)** the installation of five times as many boxes as established in the current study; and **(3)** the replacement of each nest box three times over a period of 90 years. This cost estimate may seem high, but should be considered in light of the risk of projects being delayed or halted if offset failure is identified during project implementation. A costly example of this is the indefinite delay of a highway widening project in the West of Victoria, driven in part by public backlash due to offset failure (Shyling 2017).

It is important to highlight here that the conditions of approval required nest boxes to be installed, but did not stipulate that the nest boxes must be effective (Department of Planning 2010). Despite the ecological failure of the offset and the significant resources invested, the proponent has complied with the relevant condition of approval and is unlikely to be required to remedy the offset. This distinction between offset *compliance* and offset *effectiveness* has been previously illustrated by May et al. (2016) and Sudol and Ambrose (2002). At least in Australia, offset effectiveness is not a regulatory requirement unless explicitly stated in conditions of approval. This failure in biodiversity offset governance (Maron et al. 2016) has obvious implications for the pursuit of effective and efficient offsetting in practice. The Australian Government has produced a draft policy on outcomes-based conditions (Department of the Environment and Energy 2016) but at this stage, the use of such conditions it is not mandatory. The global proliferation of offset policies indicates that offsets will continue to be used to compensate for biodiversity impacts resulting from development (Bull et al. 2013; Maron et al. 2016). We therefore argue for: **(1)** proponents to be required to demonstrate offset effectiveness; **(2)** clear lines of responsibility to be established for offset delivery, monitoring, evaluation and maintenance over the long term; and **(3)** timely and transparent reporting of offset compliance and effectiveness to the public (Maron et al. 2016; May et al. 2016). The risk, as in the example given in the previous paragraph, is that public backlash will impact on projects, even if the regulatory system fails to provide adequate guidance.

In this study, the offset for the clearing of hollow-bearing trees was the establishment of nest boxes. However, large old hollow-bearing trees have a wide range of ecological roles well beyond those of habitat provision for cavity-dependent fauna (Lindenmayer and Laurance 2016). For example, Le Roux et al. (2015) found that multiple small trees could not replicate the habitat provided by individual large trees for 29% of all bird species they observed. Indeed, hollows are but one component of habitat for many species with large old hollow-bearing trees being important for foraging (e.g. for the squirrel glider (see Crane et al. 2012) and brown treecreeper (reviewed by Higgins et al. 2001). Nest boxes clearly cannot offset these additional values and a wider range of actions will be needed to compensate for the losses of these values when large old hollow-bearing trees are cleared.

Finally, the analyses reported here highlight the critical role of both: **(1)** baseline data (which were not available in this study); and **(2)** post-implementation monitoring (see also Pickett et al. 2013) for the effective evaluation of offsets. Despite the deficiencies in the offset program reported here, it is nevertheless notable that the proponent supported both post-offset establishment monitoring as well as the reporting of the results of that monitoring. Indeed, an important part of offset policy is to rigorously assess the effectiveness of the offset with empirical data after it has been implemented. We strongly encourage the publication of outcomes of more offset monitoring programs, irrespective of the results. Indeed, several authors have noted that more is often learned from conservation failures than conservation successes (Redford and Taber 2000) and our hope is that this type of learning will inform the design and role of offsetting into the future.

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