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3 **The anatomy of a failed offset**

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22 **Word Count:** 7714 words (excluding table and appendices)

23 **Abstract**

24 Biodiversity offsetting is widely applied but its effectiveness is rarely assessed. We evaluated

25 the effectiveness of a nest box program intended to offset clearing of hollow-bearing trees

26 associated with a freeway the upgrade in southern Australia. The offset targeted three

27 threatened vertebrates: squirrel glider (*Petaurus norfolcensis*), brown treecreeper

28 (*Climacteris picumnus*) and superb parrot (*Polytelis swainsonii*). Clearing led to the loss of

29 587 tree hollows and the offset was the placement of an equivalent number of nest boxes in

30 nearby woodland (1:1 ratio). Of these, we monitored 324 nest boxes in six sample periods

31 between 2010 and 2013, yielding 2485 individual checks of nest boxes.

32 For the three target species, we found: **(1)** no records of nest box use by the superb parrot, **(2)**

33 two records of the Brown Treecreeper (0-0.76% of accessible nest boxes used per survey

34 period), and **(3)** seven records of use of nest boxes by the Squirrel Glider (0-2.1% of

35 accessible nest boxes used per survey period). Rates of nest box use by the Superb Parrot and

36 Squirrel Glider were markedly lower than rates of use of hollow-bearing trees observed in

37 other investigations. Low levels of use by target species coupled with the extent of nest box

38 attrition suggest the offset program will not have counterbalanced the loss of the hollow-

39 bearing trees.

40 We make suggestions for improving future offset programs including a greater emphasis on:

41 (1) avoiding impacts on hollow-bearing trees; **(2)** offset effectiveness as a measure of

42 compliance; and **(3)** using realistic offset ratios.

43

44 **Keywords**: Nest boxes; cavity-dependent species; south-eastern Australia; tree hollows;

45 vegetation clearing; endangered box gum grassy woodland.

46

47 **1.   Introduction**

48   Biodiversity offsetting is a widely used approach that attempts to mitigate the impacts

49 of human activities on biodiversity (Maron et al. 2016). It involves generating conservation

50 benefits in one area that aim to compensate for the impacts of a given form of development in

51 another area. However, the large and rapidly increasing literature on offsets is highlighting

52 potential problems with offsetting, such as the relatively narrow range of impacts on

53 biodiversity that can be offset (e.g. Gibbons and Lindenmayer 2007; Maron et al. 2015b;

54 Gibbons et al. 2016; Maron et al. 2016).

55   One major deficiency in much of the work on offsets is that their effectiveness is

56 rarely subject to empirical assessment after implementation (Tischew et al. 2010; Bull et al.

57 2013) (but see Pickett et al. 2013)). The loss of some kinds of natural assets can be

58 particularly difficult to offset and hence particularly important to evaluate post-hoc. An

59 example is large old trees which can take a long time to develop and which have a range of

60 key characteristics not found in small young trees, small old trees or large young trees

61 (Lindenmayer and Laurance 2016). Cavities or hollows are a critical characteristic of large

62 old trees and they are an important nesting and denning resource for a wide range of species

63 in many ecosystems globally (Fischer and McClelland 1983; Remm and Lohmus 2011).

64 Populations of large old trees with hollows are declining in a wide range of forest, savanna,

65 agricultural and urban environments around the world, often as a result of logging, land

66 clearing or other destructive activities (Lindenmayer and Laurance 2016). Offsetting is

67 sometimes used in an attempt to mitigate the effects of the loss of large old trees with

68 hollows, particularly through the establishment of nest boxes to replace the cavity provision

69 role of these trees. However, empirical assessments of the efficacy of such offsets programs

70 are lacking, particularly at large spatial scales.

71   Here we address this knowledge gap through a four-year case study of an offset in

72   southern New South Wales, south-eastern Australia which entailed the establishment of nest

73   boxes to compensate for losses of natural hollows due to the widening of Australia's most

74   heavily used interstate freeway, the Hume Highway. The Hume Highway links the nation's

75   two largest cities (Sydney and Melbourne) and its expansion had multiple ecological impacts.

76   These included removal of habitat for hollow-dependent threatened species listed at the State

77   and National level, clearing of nationally endangered temperate box gum grassy woodland,

78   and removal of hollow-bearing trees (Australian Government Department of the

79   Environment, Water, Heritage and the Arts, 2010; NSW Government Department of

80   Planning, 2010). Thousands of trees were cleared as part of the road widening, realignment

81   and construction, including many large old trees that play a range of key ecological roles

82   within box gum grassy woodland. One of the most important roles of large old trees is the

83   provision of nesting and denning habitat for an array of cavity-dependent native vertebrates

84   (Manning et al. 2006; Lindenmayer et al. 2016b). Indeed, the loss of hollow bearing trees is

85   listed as a key threatening process under the New South Wales *Threatened Species*

86   *Conservation Act (1999)* (NSW Office of Environment and Heritage 2007). In addition to the

87   impacts of establishing human infrastructure, populations of large old trees in box gum grassy

88   woodland are threatened by a range of other processes including (among others): livestock

89   grazing (Fischer et al. 2009), secondary salinity (Stirzaker et al. 2002), firewood collection

90   (Driscoll et al. 2000), and fire (Crane et al. 2016).

91   The establishment of nest boxes was one component of a broader biodiversity offset

92   strategy implemented to satisfy legislative requirements under State and National

93   environmental protection laws (Roads and Traffic Authority, 2010). Here, we focus on the

94   nest box component of the offset strategy which was designed to compensate for the loss of

95   tree hollows (Department of Environment and Climate Change Undated) (Department of

96   Planning 2010). The loss of tree hollows was compensated at a ratio of 1:1, resulting in the

97   establishment of 587 nest boxes. Criteria for the design and installation of nest boxes

98   emphasized the need to establish a diversity of nest box types characterized by different

99   entrance sizes and internal volumes, and the need to monitor patterns of nest box use and

100 occupancy (Department of Environment and Climate Change Undated).

101   Evaluating the effectiveness of an offset requires an understanding of the baseline or

102 counterfactual scenario against which the outcomes delivered by the offset are judged (Maron

103 et al. 2015b). According to State policy at the time of this development, biodiversity offsets

104 implemented in New South Wales "should aim to result in a net improvement in biodiversity

105 over time", and "enhancement of biodiversity in offset areas should be equal to or greater

106 than the loss in biodiversity from the impact site" (Department of Environment and Climate

107 Change 2008). This implies that the baseline is the biodiversity value at the impact site before

108 clearing, although in practice, offsetting in New South Wales assumes a decline of 10% on

109 average over an unspecified time horizon (Maron et al. 2015a). The criteria used to guide the

110 installation of the nest boxes (Department of Environment and Climate Change Undated)

111 http://www.environment.nsw.gov.au/biodivoffsets/oehoffsetprincip.htm) states that:

112   *To ensure success, nest-boxes must provide suitable habitat until such time that*

113 *retained trees close to the alignment develop nest hollows and cavities to replace those that*

114 *were lost.*

115 From an ecological perspective, this means that the nest boxes must be effective for between

116 50 and 100 years after installation or until significant new nest hollows develop

117 (Lindenmayer et al. 2009), and presumably provide "suitable habitat" equivalent to the

118 amount and quality of habitat provided by tree hollows prior to clearing. However, research

119 on nest boxes elsewhere in our study region suggest that occupancy of nest boxes by species

120 of conservation concern is generally low (Lindenmayer et al. 2015).

121   A key part of the offset policy underpinning this project was to establish nest boxes for

122   three threatened taxa known to occur in box gum grassy woodland adjacent to where large

123   old scattered trees were being cleared (Department of Environment and Climate Change

124   2008). These were two birds: the brown treecreeper (*Climacteris picumnus)* and superb parrot

125   (*Polytelis swainsonii*), and the nocturnal marsupial, the squirrel glider (*Petaurus*

126   *norfolcensis*). Design criteria for these nest boxes were specified in various New South Wales

127   Government documents including Overton et al. (2013) and Department of Environment and

128   Climate Change (2008).

129   Our first question in this investigation was: **Are nest boxes an effective offset for**

130   **clearing of hollow-bearing trees for the three species of conservation concern?** There

131   were two components to this evaluation: are the nest boxes used by the target species at rates

132   similar to those expected by the lost tree hollows? And is it likely that the next boxes will

133   remain suitable for the duration that the lost tree hollows would have done? Although pre-

134   clearing surveys of the impacted habitat were conducted (Abigroup 2010), these data were

135   not made available to us, and hence the occupancy of the lost tree hollows by the three

136   species of conservation concern (as well as other cavity-dependent fauna) at the impact sites

137   could not be known. To estimate the counterfactual (occupancy of natural tree hollows by the

138   species of conservation concern in the absence of tree clearing), we drew upon data from a

139   range of sources (see Section 2: Methods). At the outset of this investigation, we were

140   doubtful of the efficacy of the establishment of nest boxes as an effective offset. This was

141   because research on nest boxes elsewhere in our study region indicated a paucity of use by

142   species of conservation concern (Lindenmayer et al. 2015).

143   As part of conducting surveys of the nest boxes for the three species of conservation

144   concern, we also gathered data on nest box use by other cavity-dependent taxa. This enabled

145   us to address a second question: **What are the overall levels of nest box use and by which**

146 **species?** In answering this question and using data on covariate measures of nest boxes and

147 site-level characteristics, we also sought to quantify the factors influencing nest box use by

148 different species of cavity-dependent fauna.

149 **2.   Methods**

150 **2.1   Study area and kinds of nest boxes installed**

151   Our study area was temperate eucalypt box gum grassy woodland adjacent to the

152 Hume Highway between the towns of Coolac and Holbrook in southern New South Wales.

153 Areas of remnant native woodland and scattered hollow-bearing trees were cleared to

154 accommodate the widening of the Hume Highway. The cleared trees were estimated to

155 support 587 hollows and the corresponding offset was the establishment of 587 nest boxes.

156 These were of varying dimensions to offset the loss of a range of types of hollows, although

157 the offset did not attempt to compensate for the other habitat values of the trees that were

158 cleared. Of the 587 nest boxes, 263 could not be monitored for occupational health and safety

159 reasons such as being installed very close to the Hume Highway. We monitored the

160 remaining 324 nest boxes between 2010 and 2013 and of these, 83 were designed specifically

161 for squirrel glider, 77 for the brown treecreeper, and 37 for the superb parrot (see Appendix A

162 for design details of each box type). Other kinds of nest boxes monitored were those for bats

163 (62 boxes), the common brushtail possum *Trichosurus vulpecula* (42 boxes), the common

164 ringtail possum *Pseudocheirus peregrinus* (13 boxes) and large birds (10 boxes).

165   We inspected nest boxes in the spring of 2010, 2011, 2012 and 2013 and summer of

166 2011 and 2012, yielding 2485 individual checks of nest boxes over the four-year duration of

167 the study. During each survey, we recorded both animal presence and other signs of use such

168 as scats, hair, feathers and nests. Where there was uncertainty in identifying species from the

169 evidence of nest box use, we sent samples of scats and hair to an expert for formal

170 identification. In addition to identifying which species used the nest boxes, we also recorded

171 whether nest boxes were functional (e.g. if they had fallen to the ground) and were therefore

172 capable of being occupied or indeed in some cases whether the box was still present at all.

173 **2.2   Baseline data for the counterfactual scenario and the evaluation of offset**

174 **effectiveness**

175   The counterfactual scenario for assessing the effectiveness of nest boxes as an offset

176 demanded quantifying the occupancy of natural tree hollows by the three target species of

177 conservation concern in the absence of tree clearing. The absence of pre-clearing survey data

178 from the impacted sites meant that occupancy rates for the brown treecreeper, squirrel glider

179 and superb parrot prior to the clearing of hollow-bearing trees and the establishment of the

180 offset was not known. We therefore estimated the counterfactual scenario by drawing on data

181 from a range of other sources. Our first dataset for estimating the counterfactual scenario was

182 derived from a matched case-control study of nest trees occupied by the superb parrot in box

183 gum grassy woodland (Crane et al. 2010), including the areas where this investigation was

184 located (Manning 2004; Manning et al. 2013). That study identified 136 occupied nest trees

185 from a sample population of 2857 large old hollow-bearing trees located in 513 50 x 20m

186 plots. These data equate to 4.7% occupancy of trees with natural cavities by the superb parrot

187 during the breeding season for the species.

188   Our second dataset for analyzing the counterfactual scenario was a radio-tracking

189 study of den use by the squirrel glider within box gum grassy woodland in the broader study

190 area (Crane et al. 2008; Crane et al. 2010; Crane et al. 2012). That study showed that

191 individuals may use between 2-13 hollow-bearing trees as den and nest sites and swap

192 regularly between these trees from day to day (Crane et al. 2010). The average denning range

193 of the species in our study region (i.e. the area encompassed by the suite of nest trees used by

194 an individual) is 3.6 ha (Crane et al. 2010). Approximately one in every ten of the old, large

195 diameter hollow-bearing trees within a denning range was occupied by the species in a year,

196 although most individuals have a primary and secondary den site used most frequently with

197 other trees used less often (M. Crane, Lindenmayer and Cunningham unpublished data).

198   To the best of our knowledge, there have been no investigations specifically targeting

199 the rates of occupancy of natural cavities in trees by the brown treecreeper in our study

200 region. Other studies have indicated that the brown treecreeper uses a variety of kinds of

201 hollows for nesting, but primarily exploits dead branches, spouts, tree trunks and fallen logs

202 (Higgins et al. 2001). The species is also known to use nest boxes (Higgins et al. 2001).

203   For nest boxes to be effective, the species targeted by such programs need to occur in

204 the surrounding landscape so that animals can occupy them. Examinations of threatened

205 species profiles developed by the New South Wales Office of Environment and Heritage

206 (2017) confirmed that the offset sites occurred within the known ranges of all three species

207 targeted in this study. This corroborated data from our field surveys of the three target species

208 in the region based on spotlighting for arboreal marsupials and point interval counts for birds

209 completed in 2011 and 2013 at 68 long-term field sites within 10 km of where nest boxes had

210 been established (see Lindenmayer et al. 2016a; Lindenmayer et al. 2016c).

211 **2.3   Estimated costs of the nest box offset program**

212   We compiled information from the New South Wales Roads and Maritime Services

213 on the range of costs (in 2010 Australian dollars) associated with the establishment of the

214 nest box offset program. These included pre-establishment strategic planning, nest box

215 construction, and post-establishment monitoring.

216 **3.   Data exploration and analyses**

217 **3.1   Comparison with the counterfactual scenario**

218   To answer our first question (**Are nest boxes an effective offset for clearing of**

219 **hollow-bearing trees for the three species of conservation concern?)**, we compared rates

220 of use of nest boxes attached to trees by each of the species of conservation concern with the

221 rates of occupancy of natural hollows in trees from studies outside the areas subject to

222 clearing for highway upgrading (superb parrot and squirrel glider). Equivalent data for the

223 brown treecreeper were unavailable. For these comparisons, we included only boxes with an

224 entrance large enough to permit entry for a given species. Data on the 62 bat boxes (that have

225 a small entrance) were removed for all three target species of conservation concern. For the

226 squirrel glider and the superb parrot, we also removed data on the 77 nest boxes designed for

227 the brown treecreeper.

3.2   Overall patterns of use

229   To answer our second question (**What are the overall levels of nest box use and by**

230 **which species?**), we employed Bayesian binary logistic regression modelling to analyse

231 factors influencing nest box use by the following two groups of animals. These groups were:

232 **(1)** mammals (black rat, brush-tailed phascogale, common brushtail possum, common ringtail

233 possum, Gould's wattled bat, house mouse, sugar glider, squirrel glider, yellow-footed

234 antechinus, and unknown glider, unknown possum); and **(2)** birds (brown treecreeper,

235 common starling, crimson rosella, eastern rosella, grey shrike-thrush, white-throated

236 treecreeper, unknown bird and unknown rosella). We also modelled the five individual

237 species with sufficient presence data to facilitate further analysis (black rat, common

238 brushtail possum, common ringtail possum, yellow-footed antechinus and feral honeybees).

239   To quantify the factors influencing nest box use, we modelled the effects of the

240 following covariates: survey occasion (spring 2010, spring 2011, summer 2011, spring 2012,

241 summer 2012 and spring 2013); number of paddock trees within 500 metres; nest box type

242 (brown treecreeper, squirrel glider, superb parrot, bat, common brushtail possum, common

243 ringtail possum and large bird); the diameter of the tree to which a nest box was attached;

244 dieback score for the tree to which a nest box was attached; and distance to closest major

245 patch of native woodland vegetation. In addition, for an area of 1 ha around each nest box, we

246   measured or calculated values for: the total number of stems in the surrounding vegetation;

247   number of trees greater than 50cm in height; number of hollow bearing trees greater than

248   50m; topographic wetness index (TWI); and lithology fertility rating.

249   The response variable for all analyses was the presence/absence of the species or

250   species group of interest which we modelled using a Bayesian logistic regression with a

251   random effect for site. We chose uninformative but proper priors for the fixed effects

252   components and minimally informative but proper priors for the variance components of our

253   models. Specifically, we used Student t-distributions for the regression parameters to

254   minimize the effects of complete separation. We used a default prior for the random effect

255   standard deviation (site). We summarized the logistic regression model parameters by the

256   posterior mean and 95% credible intervals. We conducted the analysis using the brms

257   package (Buerkner 2015) in R version 3.2.1 (R Core Team 2015) using the RStudio interface

258   (RStudio Team 2015).

259   **4.   Results**

260   **4.1   Are nest boxes an effective offset for clearing of hollow-bearing trees for species**

261   **of conservation concern?**

262   We found limited or no use of nest boxes by the three species of conservation concern

263   targeted by the offsets program, including in the boxes specifically established for them. We

264   recorded no cases of nest box use by the superb parrot, including boxes specifically designed

265   for the species (Table 1). This contrasts with the values from the studies by (Manning 2004;

266   Manning et al. 2013) showing that 4.7% of hollow-bearing trees were used as nest sites by

267   the superb parrot (Fig. 1). That is, our results suggested that nest boxes are not a suitable

268   method for offsetting the loss of nest sites for this species. The superb parrot was detected at

269   2% of sites surveyed in 2011 and 13% of sites in 2013 that were located near the offset

270   impact areas.

271   Of all 324 nest boxes observed in this study, seven were used by the squirrel glider

272   across the four-year duration of our study, with the percentage use of nest boxes ranging from

273   zero to 0.6% of nest boxes per survey period (Table 1). Of the 185 nest boxes considered

274   accessible to the squirrel glider, percentage use values ranged from 0% to 2.1% per survey

275   period. Only one of the seven records of nest box use by the squirrel glider was in a box

276   specifically designed for the species. Rates of nest box use were lower than those recorded

277   for old, large diameter hollow-bearing trees within the denning range of a given individual in

278   a comparable survey period (approximately 10%) (Crane et al. 2010) (Crane et al.,

279   Lindenmayer and Cunningham unpublished data). Other things being equal, to offset the loss

280   of nesting sites for this species, at least five trees with suitable nest boxes are required for

281   every one hollow-bearing tree destroyed. The proportion of long-term sites near the offset

282   impact areas in which the squirrel glider was detected ranged from 1% in 2011 to 6% in 2013

283   (Fig. 1).

284   We recorded the brown treecreeper using two nest boxes in one survey period (0.6%

285   of nest boxes in spring 2010; see Table 1). Neither of the two records of the brown

286   treecreeper were from a box designed for the species. After removing nest boxes inaccessible

287   to the brown treecreeper, percentage use values ranged from 0% to 0.76% per survey period.

288   The brown treecreeper was present at 22 and 33% of long-term sites that we surveyed in 2011

289   and 2013, respectively (Fig. 1).

290

291   **Fig. 1.** Percentage rates of nest box use by each of the species of conservation concern

292   (denoted nest box use), rates of use of large old hollow-bearing trees from studies outside the

293   areas subject to clearing for highway upgrading (for superb parrot and squirrel glider only)

294   (denoted hollow use), and the proportion of long-term sites where each of the three target

295   species had been recorded between 2010 and 2013 (denoted site occupancy). Data on nest

296   box use excludes boxes with an entrance too small to permit entry of a given species.

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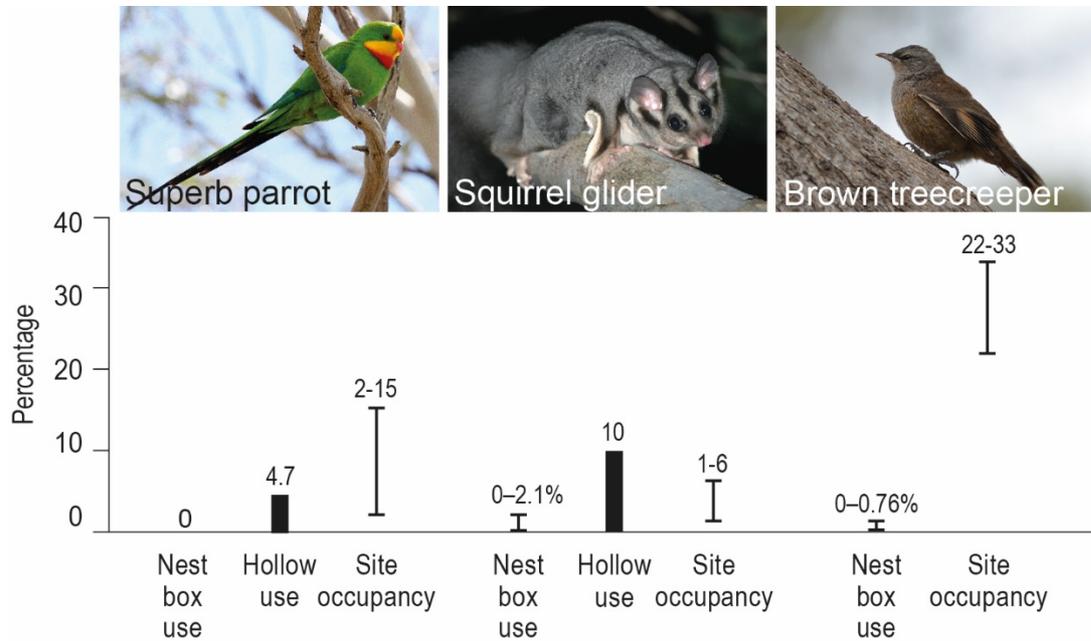
4.2   What are the overall levels of use of the nest boxes and by which species?

301   Over the four-year duration of our study and for a given survey period, between

302   44.7% and 65.1% of nest boxes contained an animal or showed signs of use (Table 1). We

303   recorded 17 species occupying the 324 nest boxes, of which four were exotic species: the

304   feral honeybee, black rat, house mouse and common starling. The most commonly recorded

305   species were the yellow-footed antechinus, with usage rates varying between survey periods

306   from 12.0-13.7%, the common brushtail possum (11.0-11.4%), feral honeybee (7.0-11.4%),

307   black rat (4.2-13.5%), common ringtail possum ((2.6%-5.7%), and common starling (0.6-

308   2.5%) (Table 1).

309

310 **Table 1:** Percentage of nest boxes where evidence of use was recorded over four years of

311 monitoring. Exotic species are marked with an asterisk*.

Common name	Scientific name	2010 Spring	2011 Spring	Summer	2012 Spring	Summer	2013 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

316   sufficient data to facilitate statistical analyses (the yellow-footed antechinus, common

317   brushtail possum, common ringtail possum, black rat and feral honeybee) (Appendix B). Nest

318   box design was a significant factor in all of the final models with marked, inter-specific

319   differences in the kinds of boxes used by different species (Appendix B). There was a

320   positive effect of the diameter of the tree to which a nest box was attached in the model for

321   the common ringtail possum but a negative effect for the black rat. The models for the

322   yellow-footed antechinus and the feral honeybee contained evidence of a positive relationship

323   between nest box use and the number of stems in the vegetation characterizing the

324   surrounding landscape. There also was evidence of season and/or year differences in the

325   proportion of nest boxes used by the common ringtail possum, black rat and feral honeybee.

326   Other significant covariates in the models we constructed included an effect of the

327   underlying lithology and topographic wetness of the sites where nest boxes were established

328   (Appendix B). The feral honeybee more often used nest boxes in locations where there was a

329   high value for the topographic wetness index whereas the reverse effect characterized the

330   model for the common ringtail possum (Appendix B).

331   **4.4   Nest box attrition**

332   Approximately 8.3% (27/324) of nest boxes became ineffective for use during the

333   four years of our study. There were several reasons for nest box failure with the two most

334   prominent being boxes falling from trees (14 boxes), and presumed theft (7 boxes).

335   **4.5   Estimated costs of the nest box offset program**

336   The development of a plan for subsequent nest box establishment cost AU\$50,000.

337   The cost of construction was AU\$200 per nest box or a total of AU\$64,800. The cost of

338   installation was AU\$262 per box or AU\$84,888 in total. Monitoring of the 324 nest boxes

339   was completed by The Australian National University under contract with the New South

340   Wales Department of Roads and Maritime Services at a total cost of AU\$64,000 or

341 approximately AU\$197.50 per box for each of six survey periods (or \$33.90 per box per

342 survey period). That is, the total cost of establishing and monitoring nest boxes under this

343 offset program was AU\$199,688.

5.   Discussion

345 The use of offsets in conservation and environmental management is widespread

346 globally (Gibbons et al. 2016; Maron et al. 2016) and is rapidly increasing (Ives and Bekessy

347 2015), but the effectiveness of such an approach has rarely been subject to empirical

348 assessment, particularly after an offset has been implemented (Pickett et al. 2013; May et al.

349 2016). We addressed this knowledge gap in the study reported here on the use of nest boxes

350 designed to offset the clearing of hollow bearing trees as part of the widening of a major

351 highway in rural Australia. Our analyses revealed that the nest box strategy examined here

352 was not sufficient to offset impacts of development on the availability of nesting sites for at

353 least two of the target species of conservation concern (i.e. squirrel glider, superb parrot), but

354 had greater utility as a method to offset the loss of nesting sites for common species. In the

355 remainder of this paper we further discuss these sobering results. We conclude with

356 suggestions for improving future offset programs.

5.1   Limited nest box use by target threatened species

358 The key finding from our empirical study was the relative paucity of records of use of

359 nest boxes by target species of conservation concern (or complete absence in the case of the

360 superb parrot) (Fig. 1). The low rates of use of trees with nest boxes relative to usage patterns

361 of hollow-bearing trees in other investigations in nearby areas, coupled with the occurrence

362 of the three species in the general area where nest boxes were established, has demonstrated

363 that the offset for these animals has largely failed. Our results are similar to those of Le Roux

364 et al. (2016) whose research in the same broad ecological community reported slightly higher

365 overall occupancy rates, but zero occupancy by threatened species (including the superb

366   parrot) and domination of nest boxes by common or exotic species. However, some of our

367   results showing low levels of occupancy for species of conservation concern differ from

368   those of other researchers who have found that nest boxes specifically designed for particular

369   taxa can support populations of those species (Goldingay et al. 2015), including the squirrel

370   glider that was targeted in our study. The reasons for the differences between studies remain

371   unclear. A possible explanation for the differences between studies may have been associated

372   with the quality of work undertaken by private contractors to install nest boxes. In particular,

373   the boxes were often were poorly attached to small diameter trees (so that the mounting

374   brackets and the box were unstable). This problem may have not only contributed to reduced

375   levels of occupancy but also contributed to the attrition of more than 8% of the nest boxes

376   over the duration of our study. An additional explanation may be that other studies such as

377   that by Goldingay et al. (2015) were undertaken in areas where the abundance of hollow-

378   bearing trees was limited and/or the population density of the species greater, and hence rates

379   of nest box occupancy may be expected to be relatively high. The duration of our study was

380   four years and it is possible that we may have achieved high rates of nest box occupancy over

381   a more prolonged period. However, other longer-running studies (Lindenmayer et al., 2015;

382   Crane et al., unpublished data), also have met with limited or no success for the species of

383   conservation concern targeted in this study. Moreover, all of the target species occur within

384   or very close to where the nest boxes were established. Both these factors suggest that a

385   longer study may not have met with more success than we have reported here.

386   **5.2   Overall patterns of nest box use and factors influencing use**

387   We found that the most common species of vertebrates using the nest boxes were

388   species that are relatively common in woodland landscapes (the yellow-footed antechinus,

389   common brushtail possum and common ringtail possum) and/or were exotic species (the feral

390   honeybee, black rat and common starling) (Table 1). Statistical models of the factors

391 affecting nest box occupancy for the five most commonly recorded species (see Appendix B)

392 typically included a combination of nest box characteristics, attributes of the site or landscape

393 surrounding where the nest box was located, and environmental features of the location (such

394 as topographic wetness index or underlying lithology). This underscores the importance of

395 factors at multiple scales affecting the probability of nest box occupancy, ranging from those

396 that corresponded to the individual nest box level, to site and landscape level features.

397   We found no evidence for a positive or negative effect on nest box occupancy of

398 variables such as the number of large old paddock trees in the surrounding landscape nor the

399 number of hollow-bearing trees within 50 metres of a nest box (Appendix B). There also was

400 no evidence of significant effects of dieback of trees in the surrounding vegetation on nest

401 box occupancy (Appendix B). The reasons for the lack of influence of these variables remain

402 unclear. Paddock trees are often used for nesting and foraging by species such as the squirrel

403 glider and superb parrot (Manning and Lindenmayer 2009; Crane et al. 2012) and at the

404 outset of the project we anticipated this variable may be important for the species in models

405 of nest box occupancy. It is possible that where such trees are prevalent, there is limited need

406 for animals to find shelter in nest boxes.

407   We found that nest boxes were sometimes occupied by species such as the black rat

408 and common starling (Table 1), which are significant vertebrate pests in Australian

409 agricultural landscapes. This has implications for offset policies because of the risks of

410 perverse outcomes such as the potential to create nesting resources for pest species, including

411 those that might compete with target species of conservation concern.

412 **5.3**   **The anatomy of a failed offset and some recommendations for improvement**

413   Several factors influenced the outcomes of the offset examined in this study. Whilst

414 the provision of nest boxes was well intentioned, we believe that future offset programs

415 might be more effective if key recommendations, outlined below, are taken into account.

416   First, the 1:1 offset ratio used to compensate tree hollows with nest boxes was

417   inadequate as it failed to account for the risk of offset failure (Maron et al. 2012; Miller et al.

418   2015; Gibbons et al. 2016). Although the time between impact and the installation of next

419   boxes was minimized (Department of Environment and Climate Change Undated) the low

420   usage rate of nest boxes we observed suggests a high offset ratio would be required to

421   achieve no net loss using this strategy. In the case of the squirrel glider and based on

422   comparable occupancy rates for natural cavities in hollow-bearing trees, multipliers of at least

423   five trees with a suitable nest box will be required to offset every one tree hollow that is

424   cleared. That is, there would need to be a substantially larger number of nest boxes installed

425   than the number of hollow-bearing trees lost in a development project to provide a benefit

426   that counterbalances the loss of nesting hollows. However, nest boxes may not replace such

427   functions at all for some species like the superb parrot.

428   The relatively high rate of attrition of nest boxes may well mean that they are

429   rendered non-functional relatively soon after they are installed and hence well before the

430   cavity-provision role of large old trees (which experience a much lower rate of attrition than

431   nest boxes [see (Crane et al. 2016)], can be offset. This was known prior to the establishment

432   of the offset; the nest box criteria developed by the Department of Environment and Climate

433   Change (undated) stated that nest boxes were likely to deteriorate after 5-10 years and needed

434   to be checked twice yearly until cavities develop in trees in the surrounding vegetation

435   (typically when trees are 80-120 or more years old). Given this, we strongly suggest that a

436   key part of offset policy must be to conduct due diligence on the likely effectiveness of a

437   given offset approach before it is undertaken. For example, this should include a detailed

438   prior assessment of previous work on the use of nest boxes by particular target species,

439   including they numbers and types of boxes that are occupied (if they are used at all) and

440   hence an appraisal of the likelihood of success (or failure) of such an offset strategy.

441   Until an effective, timely, and lasting offset for tree hollows can be demonstrated as

442   viable, we suggest that hollow-bearing trees should be treated as "red flag" attributes,

443   particularly where they support nesting sites for threatened and uncommon species, and

444   impacts avoided during developments. Where this is not feasible, we suggest that an offset

445   policy should include: **(1)** combined natural regeneration and/or establishment plantings of

446   restored woodland alongside guaranteed long-term nest box maintenance (i.e. repair or

447   regular replacement over many decades) until new cohorts of hollow-bearing trees are

448   recruited; **(2)** protection and management of areas containing mature trees that are under

449   threat from ongoing land uses; and **(3)** a suitable multiplier that accounts for the comparative

450   low rate of use of nest boxes relative to occupancy of hollow-bearing trees (see above),

451   together with the long time lag between impact and offset delivery.

452   A substantial multiplier on the number of nest boxes required, coupled with a demand

453   for long-term maintenance and regular replacement of nest boxes, means higher costs.

454   Therefore, cost effectiveness analysis should be considered when comparing potential options

455   for offsets. Indeed, the AU$199,688 expended on the largely unsuccessful nest box offset

456   program examined here was manifestly inadequate given low levels of nest box use by target

457   species and high rates of attrition of nest boxes. An approximation of the cost of making this

458   offset effective is $12.16 million dollars (in 2010 Australian dollars). This was based on the

459   cost of: **(1)** monitoring all boxes twice per year for 90 years; **(2)** the installation of five times

460   as many boxes as established in the current study; and **(3)** the replacement of each nest box

461   three times over a period of 90 years. This cost estimate may seem high, but should be

462   considered in light of the risk of projects being delayed or halted if offset failure is identified

463   during project implementation. A costly example of this is the indefinite delay of a highway

464   widening project in the West of Victoria, driven in part by public backlash due to offset

465   failure (Shyling 2017).

466   It is important to highlight here that the conditions of approval required nest boxes to

467   be installed, but did not stipulate that the nest boxes must be effective (Department of

468   Planning 2010). Despite the ecological failure of the offset and the significant resources

469   invested, the proponent has complied with the relevant condition of approval and is unlikely

470   to be required to remedy the offset. This distinction between offset *compliance* and offset

471   *effectiveness* has been previously illustrated by May et al. (2016) and Sudol and Ambrose

472   (2002). At least in Australia, offset effectiveness is not a regulatory requirement unless

473   explicitly stated in conditions of approval. This failure in biodiversity offset governance

474   (Maron et al. 2016) has obvious implications for the pursuit of effective and efficient

475   offsetting in practice. The Australian Government has produced a draft policy on outcomes-

476   based conditions (Department of the Environment and Energy 2016) but at this stage, the use

477   of such conditions it is not mandatory. The global proliferation of offset policies indicates

478   that offsets will continue to be used to compensate for biodiversity impacts resulting from

479   development (Bull et al. 2013; Maron et al. 2016). We therefore argue for: **(1)** proponents to

480   be required to demonstrate offset effectiveness; **(2)** clear lines of responsibility to be

481   established for offset delivery, monitoring, evaluation and maintenance over the long term;

482   and **(3)** timely and transparent reporting of offset compliance and effectiveness to the public

483   (Maron et al. 2016; May et al. 2016). The risk, as in the example given in the previous

484   paragraph, is that public backlash will impact on projects, even if the regulatory system fails

485   to provide adequate guidance.

486   In this study, the offset for the clearing of hollow-bearing trees was the establishment

487   of nest boxes. However, large old hollow-bearing trees have a wide range of ecological roles

488   well beyond those of habitat provision for cavity-dependent fauna (Lindenmayer and

489   Laurance 2016). For example, Le Roux et al. (2015) found that multiple small trees could not

490   replicate the habitat provided by individual large trees for 29% of all bird species they

491 observed. Indeed, hollows are but one component of habitat for many species with large old

492 hollow-bearing trees being important for foraging (e.g. for the squirrel glider (see Crane et al.

493 2012) and brown treecreeper (reviewed by Higgins et al. 2001). Nest boxes clearly cannot

494 offset these additional values and a wider range of actions will be needed to compensate for

495 the losses of these values when large old hollow-bearing trees are cleared.

496 Finally, the analyses reported here highlight the critical role of both: **(1)** baseline data

497 (which were not available in this study); and **(2)** post-implementation monitoring (see also

498 Pickett et al. 2013) for the effective evaluation of offsets. Despite the deficiencies in the

499 offset program reported here, it is nevertheless notable that the proponent supported both

500 post-offset establishment monitoring as well as the reporting of the results of that monitoring.

501 Indeed, an important part of offset policy is to rigorously assess the effectiveness of the offset

502 with empirical data after it has been implemented. We strongly encourage the publication of

503 outcomes of more offset monitoring programs, irrespective of the results. Indeed, several

504 authors have noted that more is often learned from conservation failures than conservation

505 successes (Redford and Taber 2000) and our hope is that this type of learning will inform the

506 design and role of offsetting into the future.

507 **6.   Acknowledgments**

7.   References

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