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# Loss of habitat for a secondary cavity nesting bird after wildfire

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ABSTRACT

Tree cavity dependent animals are sensitive to changes in cavity availability in forests. Fire is important in the long-term dynamics of cavity creation and loss, but there are few data on how fire impacts nesting resource availability for animals. We assessed the survival of 189 trees and 191 cavities used for nesting by an endangered secondary cavity nesting bird, the swift parrot *Lathamus discolor*, over a decade. A subset of monitored trees were burned in an uncontrolled fire. At the site of that fire, we compared swift parrot habitat quality before and after burning. We also evaluated the risk of total tree collapse due to stem destabilisation from basal scarring by calculating the critical failure stress for all monitored trees. Modelled persistence of unburned swift parrot nest cavities was more than twice that of scorched cavities over ten years. Likewise, unburned nest trees were more likely to still be standing at the end of the ten years than scorched trees. Fire caused an acute local increase in cavity and tree collapse. At the site of the fire, 62.8% of scorched nest cavities were destroyed compared to only 9.1% over the unburned remainder of the study area. Likewise, 48.6% of scorched nest trees collapsed at the fire affected site, compared to only 3.8% of unburned trees elsewhere. Burning associated tree collapse led to a significant decrease in tree diameter at breast height and number of potential cavities at monitored plots. This destroyed most of the existing nest cavity resource for swift parrots at the local scale and cavity abundance is unlikely to be replenished quickly. Loss of nesting resources may outweigh longer-term benefits of fire as an agent of cavity creation if animals miss opportunities for reproduction in locations where habitat is diminished by cumulative stochastic events and anthropogenic changes.



## 1. Introduction

Mature forests support unique habitat features like cavities in trees, which are a critically important resource for animals that use them for shelter and nesting (Newton, 1994). Tree cavities form either by animal excavation (eg. woodpeckers) or wood decay (via fungal or insect attack, weather damage and fire), but compared to the rapid creation of excavated cavities, decay-formed cavities form relatively slowly (Gibbons and Lindenmayer, 2002). Many animals that utilise cavities either cannot or infrequently excavate them, and instead rely on primary excavators and decay to provide cavities (Aitken and Martin, 2007). Nonetheless, these secondary cavity nesters are selective of cavity morphology, and sensitive to changes in availability of their preferred cavities (Aitken and Martin, 2008). Cavity abundance can be reduced by anthropogenic change (Gibbons et al., 2002), which often occurs in tandem with natural stochastic events like storms and fire (White et al., 2005; Clark et al., 2013). Cumulative disturbance events can cause the rate of cavity loss to exceed replacement, which is a serious threat for secondary cavity nesters (Lindenmayer et al., 2013).

Fire is particularly important in the creation and loss of tree cavities in forests. Fires create cavities by killing limbs or entire trees and allowing wood decay to proceed (Gibbons and Lindenmayer, 2002). Burned forests eventually experience a pulse of cavity formation after fire (Haslem et al., 2012), but given enough time and successive disturbance events, cavity bearing limbs and trees are prone to collapse because they are structurally compromised (Newton and Brockie, 1998; Gibbons et al., 2000). For instance, basal scarring due to repeated burning is common in old, cavity bearing trees (Whitford, 2002) and is an important cause of collapse in some landscapes (Gibbons et al., 2000). Cavity bearing trees are also disproportionately affected by anthropogenic change, so that in some landscapes their abundance is dramatically reduced (Lindenmayer et al., 2012). Older trees produce more cavities, and in disturbed landscapes cavity recruitment can be minimal (Manning et al., 2013). In these circumstances, the potential benefits of fire in creating cavities may be offset by the cost of fire as a driver of cavity loss, particularly if over-frequent fires kill trees

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before they grow old enough to produce cavities (Newton and Brockie, 1998).

Studies in areas where primary excavators occur have shown that although fire can destroy existing nest cavities, burned areas are attractive to excavators who quickly replenish cavity numbers (Wiebe, 2014; Nappi et al., 2015). But in areas where primary excavators are absent, data on the fate of cavities and the trees that support them are only available for some forest types and species (Lindenmayer and Wood, 2010; Saunders et al., 2014; Taylor et al., 2014). Secondary cavity nesters are threatened by cavity loss (Gibbons and Lindenmayer, 2002), so there is a need to better understand how stochastic events like fire impact their availability. We present data from a decade of monitoring cavities and trees used for nesting by an endangered secondary cavity nesting bird. Swift parrots *Lathamus discolor* are selective about the types of decay-formed tree cavities they use for nesting (Stojanovic et al., 2012; Webb et al., 2012) but suitable cavities are uncommon (Stojanovic et al., 2014a). Although swift parrots rarely nest in the same place in consecutive years (Stojanovic et al., 2015), old nest cavities can eventually be reused (Stojanovic et al., 2014b). The availability of suitable nesting sites for swift parrots across their breeding range is likely to influence their population viability (Heinsohn et al., 2015). Our objective was to: (1) estimate persistence of burned and unburned swift parrot nest trees and nest cavities over their entire breeding range over ten years, (2) compare forest characteristics before and after fire to evaluate the effect of burning on swift parrot habitat quality, and (3) estimate the likelihood of collapse of our sample of swift parrot nest trees using basal scarring as an indicator of previous fire damage. We discuss our results in the context of the management of tree cavities for populations of cavity dependent animals in landscapes already degraded by anthropogenic change.

## 2. Methods

### 2.1. Study site

Swift parrot nest trees and cavities were monitored at eight regions across their whole Tasmanian breeding range between 2005 and 2014 (Fig. 1). The study area supports a diverse range of *Eucalyptus* dominated forest types including woodlands, dry and wet forests. The study region has been extensively deforested (Hansen et al., 2013), and the impact of industrial logging on habitat availability for swift parrots has been highly controversial (Allchin et al., 2013). Regulation of these impacts is recognised as a management priority (Forest Practices Authority, 2010), but is complicated by the challenges posed by the life history strategy of swift parrots (Munks et al., 2004; Saunders and Tzaros, 2011; Webb et al., 2014; Heinsohn et al., 2015).

Region five (Fig. 1) was burned by an uncontrolled fire in March 2013. The fire burned 489 hectares of swift parrot important breeding habitat in the Meehan Range National Park and adjoining private land. Fig. 2 shows the distribution of swift parrot nests identified by Webb et al. (2012) at the 'Craigow Hill' site from Region 5 relative to the wildfire affected area. We addressed objective two (evaluate the effect of burning on swift parrot habitat quality at local scales) at Craigow Hill, which is predominantly dry, grassy, *Eucalyptus pulchella* and *E. globulus* dominated forest. A small number of nest trees elsewhere were burned in unrelated fires ($n = 5$), but only individual trees burned in those instances.

### 2.2. Nest cavity and tree fate

Swift parrot nest cavities were identified initially using behavioural cues (see Stojanovic et al., 2012; Webb et al., 2012). After 2010, when a likely nest was identified, trees were climbed using single rope techniques to confirm nesting (Stojanovic et al., 2014b, 2015). Nests discovered prior to 2010 were not climbed immediately after being found, but Stojanovic et al. (2012) found that using behavioural cues to identify nests from the ground was reliable 91.7% of the time. Nest cavities across the entire breeding range were revisited each year after their discovery for up to ten years. We recorded: (1) whether the tree and cavity had burned or not (determined by looking for fire scorching on any part of the tree, or close to the cavity), (2) whether the tree was standing or collapsed, (3) whether the nest cavity was standing or collapsed, (4) presence/absence of a concave basal scar and (if present), the ratio of wall thickness to radius of the basal cavity at breast height (the ratio $t/r$ as described by Mattheck et al., 1994) to assess collapse risk.

### 2.3. Forest characteristics before/after fire

To evaluate whether fire changed habitat quality for swift parrots at the local scale after fire, we resurveyed vegetation plots at the Craigow Hill site established as part of another study in 2005 by Voogdt (2006). Plots were 28 m radius, non overlapping, and centred either on a randomly selected nest or non-nest tree ($n = 40$ plots: 19 nest plots and 21 random plots). For trees >60 cm diameter at breast height (DBH) and within 28 m of the central tree, we followed Voogdt (2006) and recorded: (1) tree species, (2) diameter at breast height (DBH), (3) basal fire scarring (where: 0 = no fire scarring, 1 = scorched bark, 2 = cambium scorched, 3 = small concave basal scar, 4 = large concave basal scar), (4) tree form (where: 1 = sapling, 2 = regrowth, 3 = advanced regrowth, 4 = mature crown, 5 = mature with major gaps in crown due to limb loss, 6 = senescent crown major gaps and major limbs dead/dying, 7 = tree alive but crown dead and mostly collapsed, dominated by epicormic growth, 8 = tree dead, 9 = collapsed tree), (5) tree species, and (6) number of potential cavities in the crown (counted from the ground using binoculars). Stojanovic et al. (2012) found that counting tree cavities using binoculars from the ground can only provide an index of cavity abundance, and we acknowledge that our cavity counts probably overestimate true cavity availability (Stojanovic et al., 2014a). Post fire surveys were undertaken in 2013 six months after the wildfire. All field techniques were calibrated between J. Webb nee Voogdt, D. Stojanovic and H. Cook so that Voogdt's (2006) methodology was followed.

### 2.4. Data analysis

To address our first objective (persistence of nest cavities and trees) we used known fate models in program MARK (White and Burnham, 1999) to model survival of swift parrot nest trees and cavities, and treated tree and cavity collapse, and cavity destruction (eg. enlargement or damage due to being burned so that the cavity was no longer suitable for swift parrots) as equivalent to tree and cavity mortality. Cavities that were scorched, but were not substantially changed in morphology were considered to have survived fire. We fitted models separately for trees and nest cavities because partial crown collapse can result in loss of nest cavities from a standing tree. We only included trees and cavities whose fate was known (i.e. no data were censored). For trees/cavities discovered after the study began, we assumed that their earlier (unmonitored) survival was not different to trees/cavities discovered in the first year of the study, i.e. 2005. We grouped trees and cavities depending on whether or not they had been burned in the study period. We used AICc ranking to select the models with the most support and used these to estimate burned and unburned tree and cavity survival over the study period.

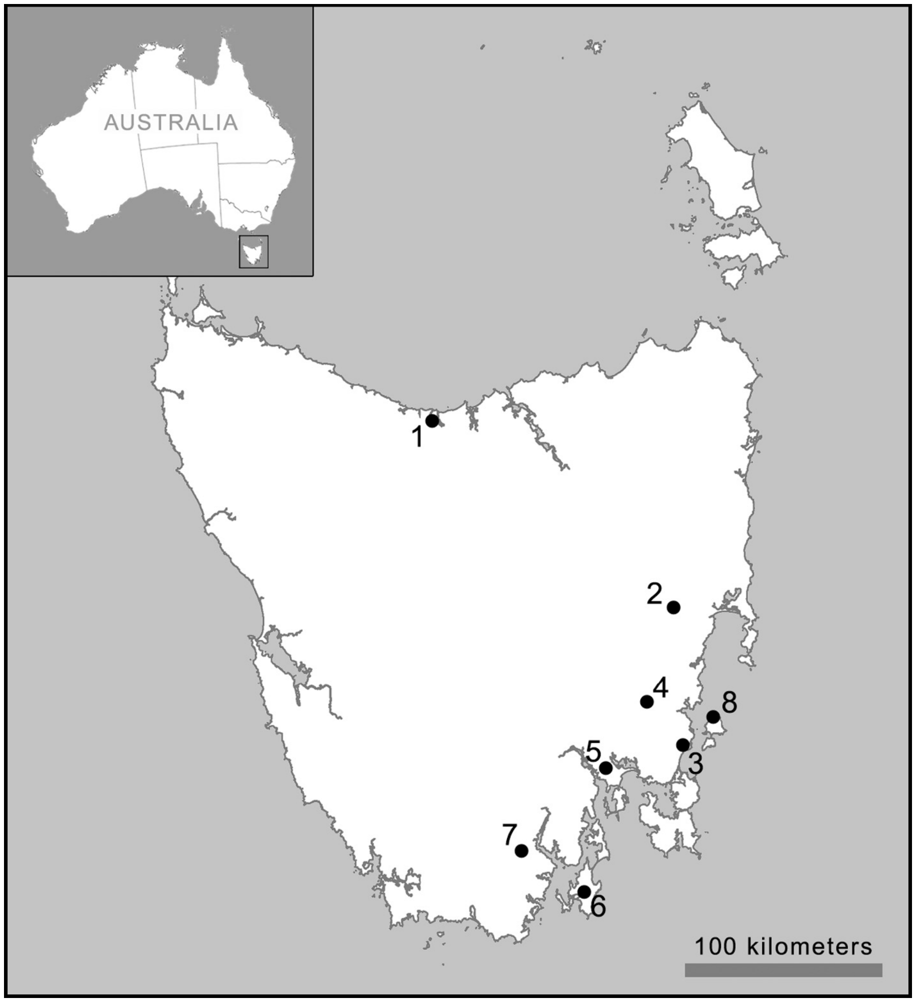


**Fig. 1.** Map of the study area showing where swift parrot nest trees were monitored: (1) Devonport, (2) Eastern Tiers, (3) Wielangta, (4) Buckland, (5) Meehan Range, (6) Bruny Island, (7) Southern Forests, and (8) Maria Island.

To address our second objective (evaluate the effect of burning on swift parrot habitat quality at local scales) we used generalized linear mixed models (GLMMs) in GENSTAT (VSN International, 2012) to evaluate the effect of plot and tree characteristics on swift parrot habitat quality at Craigow Hill. We only included plots in our analysis that burned during the wildfire. Swift parrot nest trees have a larger DBH and support more cavities than randomly selected trees (Stojanovic et al., 2012; Webb et al., 2012), so we used these two variables as indicators of plot habitat quality. We used DBH and number of cavities as response variables in two simple models where we included as additive fixed effects: plot type (nest/random), year (i.e. before/after fire), tree form and basal fire scarring (all categorical variables were treated as factors). In both models, we included Plot ID as a random term. For DBH we used a normal distribution and an identity link function in the models, but for number of cavities, we used a Poisson distribution and a logarithm link function.

To address our third objective (estimating tree collapse risk) we assessed whether swift parrot nest trees are at risk of stem failure. Mattheck et al. (1994) demonstrated that a tree stem is likely to break when the ratio of sound wood ($t$) to stem radius ($r$) falls below 0.35, a pattern confirmed by subsequent studies in forests similar to our study area (Gibbons et al., 2000). We used this relationship to evaluate $t/r$ for all standing swift parrot nest trees in our sample, so that we could identify trees at risk of collapse (i.e. trees whose $t/r$ either approached or reached 0.35). Not all trees in the sample had basal scars, so $t/r$ was only calculated for basally scarred trees.

## 3. Results

### 3.1. Tree and cavity fate

We estimated survival for 189 swift parrot nest trees and 191 nest cavities between 2005 and 2014 (there were two trees in our sample with two nest cavities). Most nest cavities included in this study presumably formed by natural decay. However, swift parrots substantially excavated two cavities in our sample (in both cases, approximately one week of excavation increased cavity depth from <5 cm to ~30 cm, and floor diameter from <5 cm to ~12 cm). We recorded swift parrots nesting in nine tree species, but most of our total sample comprised: *E. obliqua* ($n = 64$), *E. pulchella* ($n = 46$) and *E. globulus* ($n = 40$). The remainder comprised: *E. amygdylina* ($n = 11$), *E. viminalis* ($n = 10$), *E. dalrympleana* ($n = 2$), *E. regnans* ($n = 2$), *E. tenuiramis* ($n = 2$), *E. delegatensis* ($n = 1$) and unidentifiable dead stags ($n = 11$; all other trees were either alive, or dead but still identifiable to species). Of the 19.0% ($n = 36$) of nest cavities that collapsed out of the total sample,

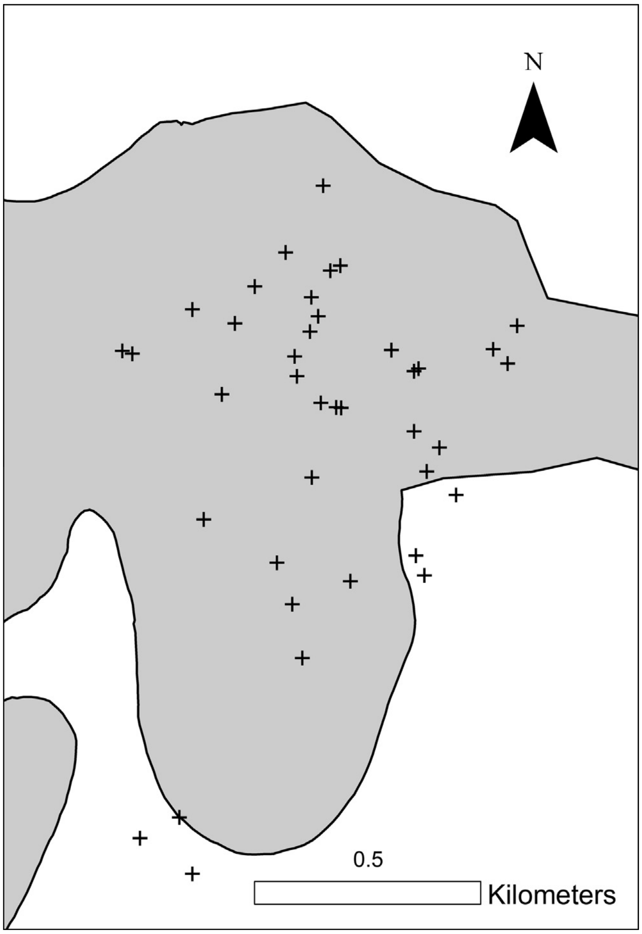


**Fig. 2.** Map of the Craigow Hill study area (Region 5, Fig. 1) showing the location of swift parrot nest trees (crosses) relative to the wildfire affected area (grey shading).

63.9% ($n = 23$) of the trees supporting those cavities also collapsed. For the remaining 36.1% ($n = 13$) of trees, partial or complete collapse of the crown caused the loss of the nest cavity.

Fire burned 22.5% ($n = 40$) of monitored nest trees, and 87.5% ($n = 35$) of these occurred on Craigow Hill. When we consider the Craigow Hill subsample, 62.8% ($n = 22$) of cavities and 48.6% ($n = 17$) of trees collapsed due to burning within six months of fire. This contrasts with only 9.1% ($n = 14$) of cavities and 3.8% ($n = 6$) of trees lost over the remainder of the study area as a consequence of illegal firewood harvesting ($n = 2$) and stem breakage ($n = 4$).

The best-supported model for tree persistence allowed survival to vary over time and depended on whether or not a tree had burned (Table 1). Using parameter estimates from this model, we estimated that decadal survival of burned trees was 0.57 (±0.08 se), and 0.96 (±0.02 se) for unburned trees. Annual estimates show that burned trees fared worse than unburned trees in the year of the fire and for the remainder of the study period (Fig. 3a and b).

The best-supported model for persistence of nest cavities allowed survival to vary over time, and depended on whether the cavity burned or not (Table 2). Using this model, we estimated that decadal survival of burned nest cavities was 0.43 (±0.08 se), and 0.91 (±0.02 se) for unburned cavities. Annual estimates show that burned cavities fared worse than unburned cavities in the year of the fire and the remainder of the study period (Fig. 3c and d).

Concave basal scars were recorded on 51.9% ($n = 98$) of standing swift parrot nest trees. We calculated that 16.3% ($n = 16$) of this group had a $t/r \leqslant 0.35$, putting them at imminent risk of collapse by stem breakage. Basally scarred trees occurred throughout the study area, but 35.3% ($n = 6$) of the high collapse risk group occurred on burned sites at Craigow Hill.

**Table 1**
Model selection for survival of swift parrot nest trees. Models are ranked according to AICc, groups refer to burned/unburned trees.

| Model | AICc | Akaike weight | Number of parameters | Model deviance |
|---|---|---|---|---|
| Group ∗ Time | 177.1106 | 1 | 20 | 0 |
| Time | 202.4461 | 0 | 10 | 45.6764 |
| Group | 219.4379 | 0 | 2 | 78.7817 |
| Constant | 249.3621 | 0 | 1 | 110.7103 |

*3.2. Forest plots*

We included data collected from 570 trees ($n = 314$ in 2005, and $n = 256$ in 2014) from the subset of burned Craigow Hill forest plots (nest plots, $n = 17$; random plots, $n = 20$) in our models. For our model of tree DBH, we found significant effects of wildfire and extent of basal scarring (Table 3) but not plot type or tree form ($p = 0.759$ and 0.355 respectively). For our model of potential number of tree cavities, we found significant effects of fire, plot type, extent of basal scarring and tree form (Table 3).

## 4. Discussion

Over a decade, swift parrot nest trees and cavities persisted at reasonably high rates, but wildfire was an important cause of tree and cavity collapse. Unburned cavities and trees mostly survived the study, but of those that burned, nearly half had collapsed within six months of the fire. At Craigow Hill (a key site within an important breeding area for swift parrots; Webb et al., 2012) wildfire caused the collapse of 62.8% of nest cavities and killed or scorched the remaining trees. Fire induced tree and cavity collapse led to a significant decrease in tree DBH and number of potential tree cavities in plots at Craigow Hill. The proportion of tree cavities used by swift parrots that were destroyed by fire at Craigow Hill is worse than that recorded in other similar study systems (Lindenmayer et al., 2012; Saunders et al., 2014). It was also substantially worse than elsewhere in our study area, where only 9.1% of cavities collapsed. In places where primary excavators occur, even though fires can destroy a significant proportion of existing tree cavities, these can be replaced in only a few years by increased rates of excavation by woodpeckers after fire (Saab et al., 2011; Wiebe, 2014). Although we observed swift parrots excavating two cavities, it is unlikely that opportunistic excavation of cavities occurs frequently enough to replace cavities that collapsed after fire. At a local scale, the Craigow Hill fire caused a substantial loss of existing nesting resources for swift parrots, with a low probability of replenishment in the near future. This may have important implications for local carrying capacity, because swift parrots aggregate when nesting (Webb et al., 2012) and it is likely that they need enough tree cavities in close proximity to enable communal settlement.

Nest plots supported significantly more potential tree cavities than non nest plots and this result supports the findings of (Voogdt, 2006). However, this is unsurprising given that swift parrot nest trees support more cavities than randomly selected trees (Stojanovic et al., 2012; Webb et al., 2012). Potential cavity numbers increased with higher tree form and basal fire scarring scores, which are both characteristics that make trees more likely to produce cavities, but also make collapse more likely (Gibbons et al.,

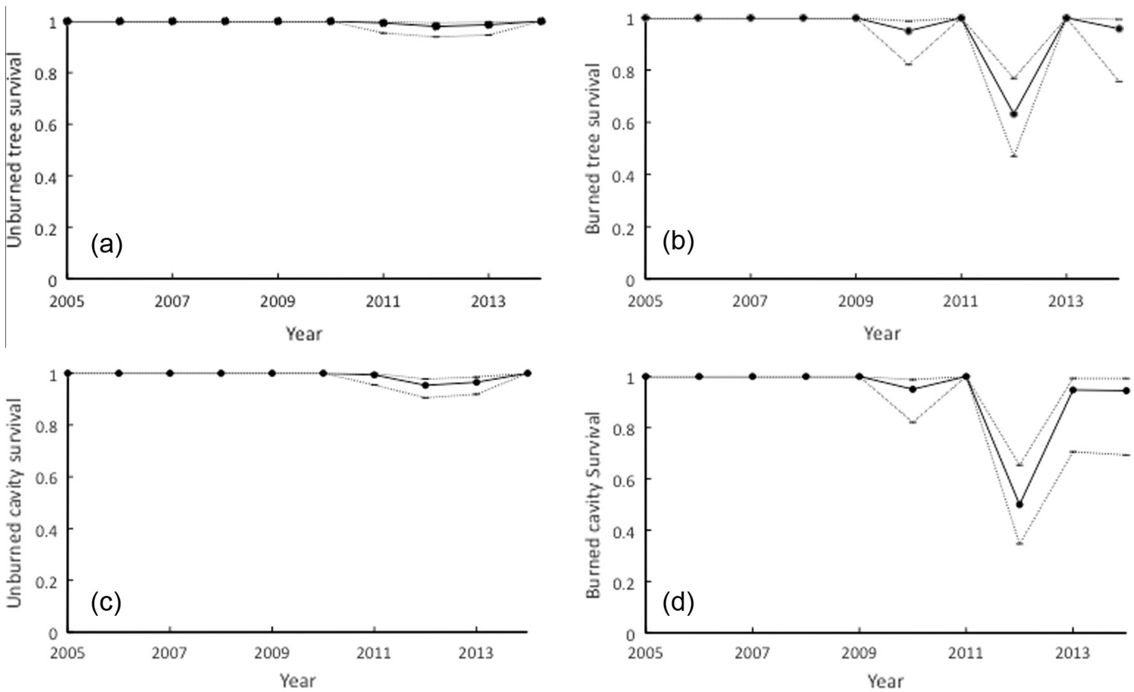


**Fig. 3.** Modelled annual survival (with confidence intervals) of unburned (a) and burned (b) swift parrot nest trees, and unburned (c) and burned (d) tree cavities used by swift parrots over the study period (ten austral summers between 2005 and 2014). A wildfire occurred at Craigow Hill (Region 5, Fig. 1) in the summer of 2012/13.

**Table 2**
Model selection for survival of swift parrot nest cavities. Models are ranked according to AICc, groups refer to burned/unburned tree cavities.

| Model | AICc | Akaike weight | Number of parameters | Model deviance |
|---|---|---|---|---|
| Group * Time | 236.5407 | 0.98703 | 20 | 0 |
| Time | 269.3322 | 0 | 10 | 53.1327 |
| Group | 323.2314 | 0 | 2 | 123.1457 |
| Constant | 356.5808 | 0 | 1 | 158.4995 |

2008). This finding is similar to those of other studies, where cavities are most abundant in older, collapse prone trees (Gibbons et al., 2008). Our findings that tree DBH in plots was lower after fire, and that larger trees were more likely to be severely basally scarred, support the evidence from our survival analysis that old, cavity-bearing trees are vulnerable to fire. Given that suitable swift parrot nesting sites are uncommon (only 5% of cavities are suitable for wildlife in our study area, Stojanovic et al., 2012, 2014a), preventative measures (eg. managing burning regimes to prevent uncontrolled wildfire, Legge et al., 2011) may be a good first step for reducing the number of potential swift parrot nests and nest trees destroyed in this way. At the local scale of our plots, the loss of large trees and potential cavities points to a decrease in local habitat quality for swift parrots as a consequence of wildfire.

More than half of the trees in our over all sample had a concave basal scar, which is a consequence of cumulative historic burning, and can double collapse risk in *Eucalyptus spp.* (Gibbons et al., 2008). Mattheck et al. (1994) showed that eucalypts whose $t/r < 0.35$ are likely to collapse due to stem breakage. By this measure, 16.3% of trees in our sample of basally scarred nest trees are at imminent risk of collapse and 35.3% of that group occur on Craigow Hill. Basal scarring occurred on trees throughout the study area, and is a common characteristic of trees in fire prone

**Table 3**
Modelled parameters for significant relationships between tree or plot characteristics and swift parrot habitat quality at Craigow Hill after wildfire. DBH refers to tree diameter at breast height.

| Response variable | Fixed effect | Wald statistic | d. f. | *P* | Modelled effect size |
|---|---|---|---|---|---|
| Tree DBH | Wildfire | 20.08 | 1 | <0.001 | Before fire: 84.73 cm<br>After fire: 72.44 cm |
| Tree DBH | Basal scar | 26.37 | 4 | <0.001 | DBH (cm) by basal scarring score:<br>0 = 70.02, 1 = 77.37, 2 = 76.8, 3 = 80.75, 4 = 87.98 |
| No. cavities | Wildfire | 31.2 | 1 | <0.001 | Before fire: 1<br>After fire: 0.5 |
| No. cavities | Plot type | 7.11 | 1 | 0.012 | Nest plot: 0.6<br>Random plot: 0.8 |
| No. cavities | Basal scar | 41.93 | 4 | <0.001 | No. cavities by basal scarring score:<br>0 = 0.4, 1 = 0.68, 2 = 0.75, 3 = 0.76, 4 = 1.26 |
| No. cavities | Tree form | 66.47 | 8 | <0.001 | No. cavities by form score: 1 = 0.24, 2 = 1.81, 3 = 1.44, 4 = 3.25, 5 = 5.20, 6 = 5.70, 7 = 4.21, 8 = 3.42, 9 = 0 |

Australian forests (Gibbons and Lindenmayer, 2002). As destabilised trees succumb to future stochastic events, swift parrot nesting habitat will continue to be lost across Tasmania. However, the collapse of basally scarred trees may be of particular importance at locations like Craigow Hill, where disturbance events have already reduced the local availability of nesting resources. This ongoing loss of nesting resources is occurring in context of widespread habitat loss for swift parrots from industrial logging, agriculture, urban development and (as recorded in this study) illegal firewood collection (Saunders and Tzaros, 2011). At local scales, cumulative losses of tree cavities from these activities is likely to seriously diminish the availability of nesting sites in disturbed forest for swift parrots, particularly given that old trees are disproportionately affected by these activities (Manning et al., 2013).

Although tree cavities are a critical resource for nesting swift parrots, there are two other environmental factors that strongly influence the quality of a given forest patch as breeding habitat.

Firstly, swift parrot settlement in a given patch of cavity bearing forest depends on the configuration of *Eucalyptus* flowering (i.e. food) across Tasmania (Webb et al., 2014; Stojanovic et al., 2015). Fire affects flowering phenology of eucalypts (Law et al., 2000), and reduced flowering in burned forest may further diminish habitat availability for swift parrots.

Secondly, swift parrots are critically endangered by intense nest predation by introduced sugar gliders *Petaurus breviceps* (Heinsohn et al., 2015). The intensity of sugar glider predation on nests may increase with decreasing cover of mature, cavity bearing forest (Stojanovic et al., 2014b). Sugar gliders were detected at Craigow Hill both before and after wildfire (Stojanovic, D. unpublished data), and understanding their tolerance of disturbance is a key research priority.

Our results demonstrate that available habitat for cavity dependent species can be severely degraded by uncontrolled fire. Cavity dependent animals, including the swift parrot, are disproportionately threatened by changes to their habitat (Gibbons and Lindenmayer, 2002) and the availability of tree cavities can limit their populations when in short supply (Newton, 1994). At Craigow Hill, local forest characteristics have shifted towards younger trees with fewer cavities as a consequence of wildfire. Slow recruitment of decay formed cavities can lead to serious resource deficits if disturbance events are too frequent (Lindenmayer et al., 2012). The conservation of threatened cavity dependent animals depends on maintaining availability of tree cavities over both the short and long term. Missed opportunities for breeding (as may occur in cavity limited habitat) may be problematic for the recovery of small or declining populations. Management intervention (eg. deployment of nesting boxes) may be necessary in cavity-limited forest to maintain habitat suitability for animals until natural cavities eventually form.

Fire has profound impacts on ecosystems, and anthropogenic changes to natural fire regimes can drastically alter community composition and structure. Across our study area, fire regimes and ecosystems have changed substantially (Bowman et al., 2013; Holz et al., 2015), and under climate change the risk of wildfire is predicted to increase (Fox-Hughes et al., 2014). Our study exemplifies the challenges facing land managers conserving threatened habitat specialists. There is a need to balance the frequency and intensity of disturbance events that can both create and destroy habitat for cavity dependant wildlife (Imbeau et al., 1999). At small spatial scales, individual stochastic events like wildfire can dramatically change the quality of habitat for secondary cavity nesters (Newton and Brockie, 1998). There is an urgent need to account for cumulative effects of anthropogenic and stochastic events on habitat quality for cavity dependent species because their combined effects have major implications for individual fitness (Nappi and Drapeau, 2009). We show that by monitoring habitat suitability for swift parrots across their entire breeding range, it is possible to detect the impact of stochastic events on the availability of a critical habitat feature, and provide land managers with detailed information to target where to invest effort for restoration. Given that swift parrots reuse nesting areas when food is available nearby (Webb et al., 2012; Stojanovic et al., 2015), the efficacy of supplementing cavity availability and protecting known nesting sites in areas where natural cavities have been destroyed warrant further investigation as management options.

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## References

Aitken, K.E.H., Martin, K., 2007. The importance of excavators in hole-nesting communities: availability and use of natural tree holes in old mixed forests of western Canada. J. Ornithol. 148, 425–S434.
Aitken, K.E.H., Martin, K., 2008. Resource selection plasticity and community responses to experimental reduction of a critical resource. Ecology 89, 971–980.
Allchin, R., Kirkpatrick, J., Kriwoken, L., 2013. On not protecting the parrot: impact of conservation and planning legislation on an endangered species in Tasmania. J. Int. Wildl. Law Policy 16, 81–104.
Bowman, D.M.J.S., Wood, S.W., Neyland, D., Sanders, G.J., Prior, L.D., 2013. Contracting tasmanian montane grasslands within a forest matrix is consistent with cessation of Aboriginal fire management. Austral Ecol. 38, 627–638.
Clark, D.A., Anthony, R.G., Andrews, L.S., 2013. Relationship between wildfire, salvage logging, and occupancy of nesting territories by northern spotted owls. J. Wildl. Manage. 77, 672–688.
Forest Practices Authority, 2010. Interim species habitat planning guideline for the conservation management of *Lathamus discolor* (Swift Parrot) in areas regulated under the Tasmanian Forest Practices System. In: Internal report to the Forest Practices Authority. Forest Practices Authority, Hobart.
Fox-Hughes, P., Harris, R., Lee, G., Grose, M., Bindoff, N., 2014. Future fire danger climatology for Tasmania, Australia, using a dynamically downscaled regional climate model. Int. J. Wildl. Fire 23, 309–321.
Gibbons, P., Cunningham, R.B., Lindenmayer, D.B., 2008. What factors influence the collapse of trees retained on logged sites?: a case-control study. For. Ecol. Manage. 255, 62–67.
Gibbons, P., Lindenmayer, D.B., 2002. Tree Hollows and Wildlife Conservation in Australia. CSIRO Publishing, Melbourne.
Gibbons, P., Lindenmayer, D.B., Barry, S.C., Tanton, M.T., 2000. The effects of slash burning on the mortality and collapse of trees retained on logged sites in south-eastern Australia. For. Ecol. Manage. 139, 51–61.
Gibbons, P., Lindenmayer, D.B., Barry, S.C., Tanton, M.T., 2002. Hollow selection by vertebrate fauna in forests of southeastern Australia and implications for forest management. Biol. Conserv. 103, 1–12.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853.
Haslem, A., Avitabile, S.C., Taylor, R.S., Kelly, L.T., Watson, S.J., Nimmo, D.G., Kenny, S. A., Callister, K.E., Spence-Bailey, L.M., Bennett, A.F., Clarke, M.F., 2012. Time-since-fire and inter-fire interval influence hollow availability for fauna in a fire-prone system. Biol. Conserv. 152, 212–221.
Heinsohn, R., Webb, M.H., Lacy, R., Terauds, A., Alderman, R., Stojanovic, D., 2015. A severe predator-induced decline predicted for endangered, migratory swift parrots (*Lathamus discolor*). Biol. Conserv. 186, 75–82.
Holz, A., Wood, S.W., Veblen, T.T., Bowman, D.M.J.S., 2015. Effects of high-severity fire drove the population collapse of the subalpine Tasmanian endemic conifer *Athrotaxis cupressoides*. Glob. Change Biol. 21, 445–458.
Imbeau, L., Savard, J.P.L., Gagnon, R., 1999. Comparing bird assemblages in successional black spruce stands originating from fire and logging. Can. J. Zool. 77, 1850–1860.
Law, B., Mackowski, C., Schoer, L., Tweedie, T., 2000. Flowering phenology of myrtaceous trees and their relation to climatic, environmental and disturbance variables in northern New South Wales. Austral Ecol. 25, 160–178.

Legge, S., Murphy, S., Kingswood, R., Maher, B., Swan, D., 2011. EcoFire: restoring the biodiversity values of the Kimberley region by managing fire. Ecol. Manage. Restor. 12, 84–92.

Lindenmayer, D., Blanchard, W., McBurney, L., Blair, D., Banks, S., Likens, G., Franklin, J., Laurance, W., Stein, J.A., Gibbons, P., 2012. Interacting factors driving a major loss of large trees with cavities in a forest ecosystem. PLoS ONE 7, e41864.

Lindenmayer, D.B., Laurance, W.F., Franklin, J.F., Likens, G.E., Banks, S.C., Blanchard, W., Gibbons, P., Ikin, K., Blair, D., McBurney, L., Manning, A.D., Stein, J.A.R., 2013. New policies for old trees: averting a global crisis in a keystone ecological structure. Conserv. Lett. 7, 61–69.

Lindenmayer, D.B., Wood, J.T., 2010. Long-term patterns in the decay, collapse, and abundance of trees with hollows in the mountain ash (*Eucalyptus regnans*) forests of Victoria, southeastern Australia. Can. J. For. Res. 40, 48–54.

Manning, A.D., Gibbons, P., Fischer, J., Oliver, D.L., Lindenmayer, D.B., 2013. Hollow futures? Tree decline, lag effects and hollow-dependent species. Anim. Conserv. 16, 395–403.

Mattheck, C., Bethge, K., West, P.W., 1994. Breakage of hollow tree stems. Trees 9, 47–50.

Munks, S.A., Richards, K., Meggs, J.M., Brereton, R.N., 2004. The importance of adaptive management in 'off-reserve' conservation for forest fauna: implementing, monitoring and upgrading Swift Parrot *Lathamus discolor* conservation measures in Tasmania. In: Lunney, D. (Ed.), Conservation of Australia's Forest Fauna, second ed. Royal Zoological Society of New South Wales, Mosman, pp. 688–698.

Nappi, A., Drapeau, P., 2009. Reproductive success of the black-backed woodpecker (Picoides arcticus) in burned boreal forests: are burns source habitats? Biol. Conserv. 142, 1381–1391.

Nappi, A., Drapeau, P., Leduc, A., 2015. How important is dead wood for woodpeckers foraging in eastern North American boreal forests? For. Ecol. Manage. 346, 10–21.

Newton, I., 1994. The role of nest sites in limiting the numbers of hole-nesting birds: a review. Biol. Conserv. 70, 265–276.

Newton, I., Brockie, K., 1998. Population Limitation in Birds. Elsevier Science, Burlington.

Saab, V.A., Russell, R.E., Rotella, J., Dudley, J.G., 2011. Modeling nest survival of cavity-nesting birds in relation to postfire salvage logging. J. Wildl. Manage. 75, 794–804.

Saunders, D., Mawson, P., Dawson, R., 2014. Use of tree hollows by Carnaby's Cockatoo and the fate of large hollow-bearing trees at Coomallo Creek, Western Australia 1969–2013. Biol. Conserv. 177, 185–193.

Saunders, D.L., Tzaros, C., 2011. National Recovery Plan for the Swift Parrot *Lathamus discolor*. In. Birds Australia, Melbourne.

Stojanovic, D., Koch, A.J., Webb, M., Cunningham, R.B., Roshier, D., Heinsohn, R., 2014a. Validation of a landscape-scale planning tool for cavity dependent wildlife. Austral Ecol. 39, 579–586.

Stojanovic, D., Terauds, A., Westgate, M.J., Webb, M.H., Roshier, D., Heinsohn, R., 2015. Exploiting the richest patch has a fitness payoff for the migratory swift parrot. J. Anim. Ecol. http://dx.doi.org/10.1111/1365-2656.12375.

Stojanovic, D., Webb, M., Alderman, R., Porfirio, L., Heinsohn, R., 2014b. Discovery of a novel predator reveals extreme but highly variable mortality for an endangered bird. Divers. Distrib. 20, 1200–1207.

Stojanovic, D., Webb, M.H., Roshier, D., Saunders, D., Heinsohn, R., 2012. Ground-based survey methods both overestimate and underestimate the abundance of suitable tree-cavities for the endangered swift parrot. Emu 112, 350–356.

Taylor, J.E., Ellis, M.V., Rayner, L., 2014. Growth, recruitment and attrition of Eucalyptus tree species in semi-arid temperate woodland. For. Ecol. Manage. 331, 25–34.

Voogdt, J., 2006. Characteristics of Swift Parrot (Lathamus discolor) nesting habitat. In: Department of Biology, School of Zoology and Anthropology. Georg-August-University of Göttingen, Germany.

VSN International, 2012. GenStat for Windows, 15th ed. VSN International, Hemel Hempstead, UK.

Webb, M.H., Holdsworth, M.C., Webb, J., 2012. Nesting requirements of the endangered swift parrot (*Lathamus discolor*). Emu 112, 181–188.

Webb, M.H., Wotherspoon, S., Stojanovic, D., Heinsohn, R., Cunningham, R., Bell, P., Terauds, A., 2014. Location matters: using spatially explicit occupancy models to predict the distribution of the highly mobile, endangered swift parrot. Biol. Conserv. 176, 99–108.

White, G., Burnham, K., 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46 (Suppl.), 120–139.

White, T.H., Collazo, J.A., Vilella, F.J., Guerrero, S.A., 2005. Effects of hurricane Georges on habitat use by captive-reared Hispanolian Parrots (*Amazona ventralis*) released in the Dominican Republic. Ornitol. Neotrop. 16, 405–417.

Whitford, K.R., 2002. Hollows in Jarrah (*Eucalyptus marginata*) and Marri (*Corymbia calophylla*) trees: I. Hollow sizes, tree attributes and ages. For. Ecol. Manage. 160, 201–214.

Wiebe, K.L., 2014. Responses of cavity-nesting birds to fire: testing a general model with data from the Northern Flicker. Ecology 95, 2537–2547.