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The responses of a critically endangered mycophagous marsupial (*Bettongia penicillata*) to timber harvesting in a native eucalypt forest

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ABSTRACT

Mycophagous bioturbators provide ecosystem services that can be important for the resilience and restoration of ecosystems. Among the Australian mammals, mycophagy is most prevalent within the Potoroidae (bettongs and potoroos). However, proportionally more species of Potoroidae are either recently extinct or currently threatened than any other mammalian family in Australia, and they are among the least studied. The critically endangered woylie, or brush-tailed bettong (*Bettongia penicillata*), is a mycophagous, ground dwelling 'ecosystem engineer' that was one of Australia's most abundant and widely distributed potoroids prior to European settlement. After substantial range contraction, however, the remaining indigenous populations are now restricted to eucalypt forests in south-western Australia. Using an experimental approach, we investigated the population responses of the woylie to timber harvesting in these forests. Nine treatments, including varying logging intensities and unharvested controls, were applied at 22 sites. The abundance of the woylie in the harvested areas, in unharvested stands between logged areas, and in extensive unharvested stands outside the harvest management area were compared using a replicated before-after-control-impact (BACI) repeated measures design and capture-mark-recapture modelling. A total of 5860 captures of 815 individuals were recorded during 35 trapping sessions over 16 years (one year preceding, two years during, and 13 years after disturbance). Capture rate was a good index of abundance for this species and woylie abundance, survivorship and recruitment were not adversely affected by silvicultural practices in the jarrah (*Eucalyptus marginata*) forest. On the contrary, the harvested areas may have afforded some localised protection when an unrelated, species-wide decline began three years after harvesting disturbance ended; woylie numbers declined by up to 77% and 95% in harvested and unharvested areas, respectively. Thus the nature and spatial extent of the timber harvesting regimes investigated in this study were not a major threatening process for this species. However, ongoing monitoring and evaluation are necessary to ensure that timber harvesting activities remain benign in the face of a changing climate, possible increased mortality from introduced predators, disease, and further declines in the abundance of this critically endangered marsupial.

1. Introduction

The importance of mycophagous bioturbators (e.g. mammals that dig for hypogeous (underground) fungi) is becoming increasingly recognised as their key role in promoting ecosystem functioning is better understood. Ecosystem services provided by these so-called 'ecosystem engineers' include changes to soil properties (e.g. nutritional, chemical, structural and hydrological factors), the creation of seed beds, and the dispersal of the spores of important mycorrhizal fungi and the seeds of many plants (e.g. Garkaklis et al., 2004; Claridge et al., 2007; Fleming et al., 2014). Such species are therefore likely to have a significant effect on the resilience and ability of ecosystems to respond and recover from disturbances (e.g. Eldridge et al., 2009; Davidson et al., 2012; Schickmann et al., 2012). They can also have an important role in ecosystem restoration of modified or degraded landscapes and/or ecosystems under stress due to other environmental changes, such as anthropogenic disturbances including logging, fragmentation,

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grazing from introduced animals, and climate change (e.g. Romero et al., 2015). A greater understanding of the ecological functions and values of mycophagous and digging mammals could help substantially in the development of efficient and effective ecosystem and natural resource management as well as species and community conservation.

Many small mammals are obligate, preferential or opportunistic mycophagists, including species of shrew, hare and rabbit, chipmunk and squirrel, kangaroo rat, vole, rat and mouse, and many marsupials (Fogel and Trappe, 1978; Claridge and May, 1994; Claridge et al., 1996; Maser et al., 2008; Schickmann et al., 2012). Among the Australian mammals, mycophagy is most prevalent within the Potoroidae (bettongs and potoroos) (Claridge and May, 1994), with the hypogeous truffle-like forms of mycorrhizal fungi being a major component of their diets (Claridge, 2002). They are also among the least studied (Claridge and Barry, 2000) and proportionally more species are recently extinct or threatened than any other mammalian family in Australia (69% of Potoroidae compared with 12–40% for other families) (Woinarski et al., 2014). Understanding the responses of these species to timber harvesting is therefore particularly important for ongoing species conservation and ecologically sustainable forest management (ESFM) more broadly.

Globally, the effects of native timber harvesting on small mammal species richness and abundances is variable and generally species-specific, with some taxa being disadvantaged while many are not (e.g. Zwolak, 2009; Michał and Rafał, 2014). With respect to mycophagous mammals, at least some forms of forest management can adversely affect some species including the red-backed voles (*Myodes gapperi* and *Myodes californicus*), northern flying squirrel (*Glaucomys sabrinus*) and red squirrel (*Tamiasciurus hudsonicus*) of North America (e.g. Fisher and Wilkinson, 2005; Gitzen et al., 2007; Zwolak, 2009; Holloway et al., 2012), and the yellow-necked mouse (*Apodemus flavicollis*), gray-sided vole (*Myodes rufucanus*), Siberian flying squirrel (*Pteromys volans*) and Eurasian red squirrel (*Sciurus vulgaris*) of Europe (Michał and Rafał, 2014).

Many forest-dwelling, mycophagous mammals in eastern Australia, including several potoroid (*Aepyprymnus rufescens, Potorous longipes, Potorous tridactylus*) and perameliid species (*Isoodon macrourus, Isoodon obesulus*, *Perameles nasuta*), are thought to have a general preference for forests that were either undisturbed or minimally disturbed by fire or timber harvesting (Cork and Catling, 1996; Catling et al., 2000, 2001; Claridge and Barry, 2000; Coops and Catling, 2002; Kavanagh and Stanton, 2005). For most of these species, these findings are consistent with their association with structurally complex habitats, and the simplification and/or thinning of the vegetation resulting from these disturbances reduces their suitability as habitat. In contrast, the rufous bettong (*A. rufescens*) occurs predominantly in open forests and woodlands, and disturbances in these habitats tend to increase the vegetation complexity/density (Kavanagh and Stanton, 2005). Consequently, bettongs are generally considered to prefer more open habitats than potoroos, and bettongs and potoroos are thought to be disadvantaged by factors that respectively increase or decrease the complexity and density of ground vegetation (Claridge et al., 2007). These generalisations are consistent with timber harvesting not previously being considered a major threat for the woylie (*Bettongia penicillata*) in Western Australia (Start et al., 1995; Morris et al., 2001; Abbott and Whitford, 2002; Wayne et al., 2011; Yeatman and Groom, 2012), in contrast to other potoroids (e.g. *Bettongia tropica, P. longipes, P. tridactylus*), and perameliids (e.g. *I. o. obesulus*) (Woinarski et al., 2014). While these studies remain fundamentally important in providing an understanding of the ecology of these and other species, they have all been based on observational and/or time for space approaches. However, experimental studies that directly measure the responses of populations to disturbance provide greater rigour than an observational approach. Although experimental studies have been published for many other Australian fauna species (e.g. Kavanagh and Webb, 1998), direct measures of the responses of the potoroids and perameliids have been noticeably neglected. This may in part be explained by the cryptic nature of many of these species, their low densities and patchy distributions, and generally restricted ranges. Together, these factors make it particularly challenging to obtain the sample sizes needed to provide reasonable inferences.

The relatively high abundances of woylies in the 1990s and their highly trappable nature (Wayne et al., 2008) presented an opportunity apparently unique among the potoroids and perameliids to experimentally investigate their responses to timber harvesting. Consequently, determining how the woylie responds to timber harvesting provides a test for the principles of ESFM and can inform how other, more cryptic, potoroids and terrestrial mycophagous mammals may respond to timber harvesting. Therefore, the aim of this study was to experimentally test whether the silvicultural treatments associated with timber harvesting applied in jarrah forest of Western Australia adversely impacted on the abundance, survivorship and recruitment of the woylie.

2. Methods

2.1. Study species

Six of the 13 Australian potoroid species present at the time of European settlement occurred in south-western Australia. However, only two species remain in the region and both are *Critically Endangered* – the woylie (*B. penicillata*) and Gilbert's potoroo (*Potorous gilbertii*). While the Gilbert's potoroo is restricted to non-forest habitats, an estimated 90% of the woylies extant in 1999 were in jarrah (*Eucalyptus marginata*) forest habitats (Wayne et al., 2013). Of the 1.8 million ha of jarrah forest remaining, most of the 87% that is publicly vested has been subject to timber harvesting in the past (Herberle, 1997) and 48% remains available for timber harvesting (Conservation Commission of Western Australia, 2013).

The woylie is a nocturnally active, terrestrial marsupial (1300 g mean adult body mass) that each dig ~5*t* of surface soil per year foraging for their staple diet, hypogeous fungi (Garkaklis et al., 2004). Since 1999 it has undergone an acute decline (>90%) in abundance (Wayne et al., 2013, 2015). While the leading hypothesis is that this decline is due to a resurgence in predation by introduced predators (cat, *Felis catus* and European red fox, *Vulpes vulpes*) of individuals possibly made more vulnerable by disease, the cause(s) is not yet verified (Wayne et al., 2013, 2015; Marlow et al., 2015). Introduced predators, habitat loss and change due to disturbance, disease, and changed fire regimes are among the principal factors thought to be responsible for earlier declines (Wayne et al., 2015).

2.2. Study area

This study was conducted within the southern jarrah forest bioregion, in the Kingston, Warrup and Winnejup State forest blocks, 26 km north east of Manjimup, Western Australia (Fig. 1). The region experiences a Mediterranean-type climate with warm dry summers and cool wet winters, with a long-term average rainfall of ~900 mm. The topography is gently undulating with plateaux tops, low laterite ridges and broad valleys between 200 m and 340 m above sea level. Dry open forests and woodlands are dominated by jarrah and marri (*Corymbia calophylla*) overstorey