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Long-term and large-scale control of the introduced red fox increases native mammal occupancy in Australian forests

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ABSTRACT

Management agencies commonly control non-native mammalian predators to protect native prey populations, but there are few robust examples of such control enhancing native prey populations. We conducted a 9-year landscape-scale management experiment to evaluate the benefits of controlling the invasive red fox (*Vulpes vulpes*) to low densities for three native ground-dwelling mammalian prey species—common brushtail possum (*Trichosurus vulpecula*), long-nosed potoroo (*Potorous tridactylus*) and southern brown bandicoot (*Isoodon obesulus*)—in south-east Australian forests. We hypothesized that sustained and spatially extensive fox control would reduce fox abundance and increase occupancy, colonization and persistence rates for all three prey species in three treatment areas relative to three non-treatment areas. There was a substantial decline in bait take by foxes in treatment areas from 2005 to 2013, and fox abundances were much lower in treatment than non-treatment areas throughout the experiment. Occupancy rates of all three native prey species increased in treatment areas relative to non-treatment areas, although the magnitude of the increase varied with species, treatment area, and time. Colonization and persistence rates were not always positive for all species and all treatment areas. Our experiment demonstrates that foxes can be reduced to, and maintained at, low abundances and that this has a generally positive effect on the occupancy by small native mammalian prey species.
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1. Introduction

Introduced mammalian predators can dramatically reduce the distribution and abundance of their native prey, sometimes resulting in extinction (Courchamp et al., 2003; Salo et al., 2007, 2010). Native prey may lack the co-evolved adaptations needed to avoid encounters with introduced predators or that increase the probability of escape once detected by the predator (Lima and Dill, 1990; Norrdahl and Korpimäki, 2000). Predators can also have sub-lethal effects on prey behavior and physiology through stress (Boonstra et al., 1998). Predation can act to limit population growth directly by reducing recruitment and survival rates, either when the prey species is the main food item and is consumed as prey density increases, or when prey are a secondary item and are actively sought as primary prey density increases (Pech et al., 1995; Sinclair et al., 1997).

Management agencies commonly attempt to control introduced mammalian predators with the objective of minimizing their predation on native prey species (e.g. Cote and Sutherland, 1997; Glen and Dickman, 2005; Harding et al., 2001; Kinnear et al., 2010). Given that conservation resources are limited, management agencies must demonstrate that these often-substantial investments in long-term and large-scale predator control provide the hypothesized benefit (Parkes et al., 2006; Walsh et al., 2012). However, experimental designs that enable robust inference about the benefits of the predator control for native prey are seldom implemented, and hence there is uncertainty about the benefits of invasive predator control (Hone, 1999; Reddiex and Forsyth, 2006; Saunders and McLeod, 2007). In particular, few long-term and large-scale programs have replicated treatment and non-treatment areas with monitoring of both predator and prey species (Reddiex and Forsyth, 2006).

The red fox (*V. vulpes*) is a medium-sized predator (5–8 kg) that was introduced into Australia in the late 1800s and is now widespread in the southern half of that continent (Saunders et al., 1995). The fox has been implicated as a primary cause of the complete or regional extinction of a range of native mammal species in

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Australia, most of which are small- to medium-sized (35–5500 g) and ground dwelling (Burbidge and McKenzie, 1989; Johnson et al., 2007; Kinnear et al., 2002; Short and Smith, 1994). A recent review concluded that the impact of predation by the red fox on the Australian native fauna was greater than in any other area where foxes had invaded (Salo et al., 2010). Fox control, most commonly using poison baiting, is conducted with the objective of protecting native species from predation on approximately 10.5 million ha of Australia (Reddiex et al., 2006). Control is thought to reduce fox abundances when undertaken continuously over large areas (i.e. long-term and large-scale; Salo et al., 2010; Saunders and McLeod, 2007), but measuring the effects of control at these spatial and temporal scales is logistically and financially difficult. Occupancy (an estimate of the proportion of sites in an area that are occupied) is one metric that often reflects the current state of a population (MacKenzie et al., 2003). Occupancy of locations is determined by the processes of species persisting at sites from one year to the next, and the colonization of new, previously unoccupied sites. Occupancy modeling has been used to assess changes in occupancy associated with predator–prey and predator–predator interactions (Cove et al., 2012; Frey et al., 2011; Lazenby and Dickman, 2013), but to our knowledge has not been used to evaluate the effects of invasive predator control on native prey populations within a landscape-scale management experiment.

The objective of this study was to experimentally evaluate the effects of 9 years of spatially extensive red fox control on fox abundances and marsupial prey occupancy rates in a south-east Australian forest landscape. The Glenelg Ark project was established in July 2005 to facilitate the recovery of native animal populations considered at risk from fox predation by undertaking landscape-scale, continuous fox baiting across 100 000 ha of public land in the State of Victoria (Robley et al., 2011). Three prey species that were initially present in low abundances (Robley et al., 2011)) and with patchy distributions in Victoria (Menkhorst, 1995) were monitored: the southern brown bandicoot (*I. obesulus*), the long-nosed potoroo (*P. tridactylus*) and the common brushtail possum (*T. vulpecula*). All three species are killed and eaten by foxes in south-east Australia (Seebeck, 1978; Triggs et al., 1984). The southern brown bandicoot and the long-nosed potoroo are medium-sized ground-dwelling marsupials (1.0 kg and 1.2 kg, respectively) with high and moderate fecundity, respectively (Lobert and Lee, 1990). Both species have been reported to increase in abundance when foxes are controlled (Arthur et al., 2012; Kinnear et al., 2002). The common brushtail possum is a semi-arboreal species weighing 3.0 kg; it has low fecundity (Kerle and How, 2008), is known to occur in the diet of foxes, and populations are thought to increase following fox control (Kinnear et al., 2002). We tested two predictions: first, that fox abundances would be substantially reduced by baiting in the treatment areas relative to the non-treatment areas; second, that colonization, persistence and occupancy rates of the three native prey species would increase in treatment areas (where foxes were controlled to low abundances) relative to non-treatment areas (where foxes were not controlled and were at high abundances).

2. Material and methods

2.1. Study design

Our study was conducted in three treatment areas and three non-treatment areas in south-west Victoria, Australia (38°07′50″S 147°37′45″E; Fig. 1). The main vegetation communities are heathy woodland, lowland forest, herb-rich woodland, and wet heathland (Department of Sustainability and Environment, 2007). The study area has an annual mean minimum temperature of 8.1 °C in winter, an annual mean summer maximum temperature of 20.0 °C, and a mean annual rainfall of 835 mm (Bureau of Meteorology, 2014).

Wild dogs/dingoes (*Canis dingo*/*C. familiaris*) and their hybrids are considered an apex predator in south-east Australian forests (Colman et al., 2014) but were never observed in our study areas. Feral cats (*Felis catus*) are a potentially important predator of native species in Australia (Abbott, 2002) and were present in all of our study areas. However, too few were detected to be included in our study design and analyses.

The key criteria for selecting treatment and non-treatment areas were: no prior fox control, and similar fire histories and Ecological Vegetation Classes (EVC). EVC is a vegetation classification for assessing biodiversity conservation at the landscape scale in Victoria (Department of Sustainability and Environment, 2007) and closely matches habitat descriptions for the three native prey species (Bennett, 1993; Norton et al., 2010; Rees and Paull, 2000). Randomization of treatment and non-treatment areas was not logistically feasible, as all treatment areas were located in the southern half of the study area (Fig. 1). The six monitoring areas were: Southern Lower Glenelg National Park (treatment, 8954 ha), Cobboboonee National Park (treatment, 9750 ha), Mount Clay State Forest (treatment, 4703 ha), Northern Lower Glenelg National Park (non-treatment, 4659 ha), Annya State Forest (non-treatment, 8520 ha) and Hotspur State Forest (non-treatment, 6940 ha). The two Lower Glenelg National Park areas are separated by the Glenelg River, and the remaining areas are separated by open agricultural lands and an average distance of 10 km (Fig. 1).

2.2. Fox control

Fox control was undertaken in the three treatment areas using a manufactured bait (FoxOff®, Animal Control Technologies, Somerton) containing 3 mg of sodium mono-fluroacetate (1080). A single bait was buried at a depth of 10 cm, and baits were spaced at 1-km intervals along accessible forest tracks (Fig. 1). Control began in October 2005, with all baits checked and replaced fortnightly until November 2013.

2.3. Monitoring changes in fox abundance

We used non-toxic bait take as an index of fox abundance (Thompson and Fleming, 1994) in all six areas for 10 weeks immediately prior to commencing poisoning in 2005. Progressively higher non-toxic bait take occurs with time because foxes become familiar with the location of bait stations (Thompson and Fleming, 1994). The assessment period for the pre-toxic index of fox abundance commenced when variation in daily non-toxic bait take had stabilized at <15% daily variation. After arcsine transformation of the data, we used a *t*-test to determine if the fox abundance index was different in treated areas compared with non-treated areas prior to the commencement of poison baiting on the treatment sites in October 2005.

A post-poison baiting index was calculated over 10 weeks following the commencement of poisoning. The percentage change in the proportion of baits taken between the pre- and post-baiting periods on the treatment sites was estimated as:

$$\%\text{change} = \frac{(\text{pre-baiting index} - \text{post-baiting index})}{\text{pre-baiting index}} \times 100\%. \qquad (1)$$

Non-toxic baiting was repeated in the non-treatment areas annually in autumn from 2005 to 2013 in the same manner as described for the pre-toxic-baiting assessment.

We used a generalized linear mixed-effects model (GLMM) to evaluate the proportion of non-toxic baits taken in autumn between

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