Wildlife Research **2017**, *44*, 114–126
doi:10.1071/WR16178_AC

Supplementary material

Falling apart? Insights and lessons from three recent studies documenting rapid and severe decline in terrestrial mammal assemblages of northern, south-eastern and south-western Australia

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Supplement 1: Summary of the monitoring protocols for the three independent programs

1. Northern Australia

The primary focus of this study was the large (20,000 km^2) Kakadu National Park in the Northern Territory, Australia, with broader context provided by comparable monitoring programs in the nearby (ca. 150 km distant, ca. 1500 km^2) Litchfield National Park (Woinarski *et al.* 2004; Russell-Smith *et al.* 2014). The study area lies within the monsoonal tropics and has a strongly seasonal climate with annual rainfall varying across the area from ca. 800 to 1600 mm. It includes parts of the rugged sandstone Arnhem Plateau and more extensive lowland areas. Major habitats include a range of eucalypt savanna woodlands, but there are also substantial areas of floodplain grasslands, heathlands and monsoon rainforests.

Detailed accounts of the sampling protocols, and analyses of the results, are presented elsewhere (Braithwaite and Muller 1997; Woinarski *et al.* 2001; Edwards *et al.* 2003; Russell-Smith *et al.* 2009; Woinarski *et al.* 2010; Woinarski *et al.* 2012). The Kakadu monitoring program is based on 136 0.25 ha sites spread representatively across the park, and sampling the range of vegetation types present. All monitoring sites were sampled in the period 2001-04 and re-sampled in the period 2007-09. Fifteen of the sites were also initially sampled in 1996. The monitoring program has continued subsequently, with another full range of sampling undertaken over the period 2012-15. Results from that sampling have not yet been analysed fully and are not included here, but preliminary findings indicate no recovery in the native mammal fauna subsequent to the 2007-09 sampling period, and that many mammal species are now so rarely reported in the sampling that the design has become insufficiently powerful to detect trends for these species (G. Gillespie *pers. comm.*).

Mammal sampling is mainly based on live-trapping (using a consistent array of Elliott, cage and pitfall traps over a 3-night period), supplemented by two spotlight searches per site. Because of the focus on trapping, the information obtained for larger mammals (macropods, dingoes) was limited. For other species, the abundance measure used was the tally of individuals captured and observed over the sampling episode.

The sampled mammal assemblage was diverse, with 24 native (and one non-native) species reported. This tally includes all non-volant mammals known to be still present in the study area (Woinarski and Winderlich 2014).

Some factors that may affect this mammal assemblage were assessed (correlatively) during this monitoring program, but others were not directly assessed. The primary management focus in the study area was an attempt by managers to improve fire regimes, through lighting early dry season fires in order to decrease the frequency and extent of the typically more intense late dry season fires. This was partly

achieved in the sandstone environments (Murphy *et al.* 2015), but there was little consequential change in lowland fire regimes (Woinarski and Winderlich 2014), where about 50% is burnt per year and there is consequently little area remaining unburnt for >3 years. Of other potential factors affecting the native mammal fauna, there is no management of the only introduced predator (feral cat *Felis catus*), but some periodic controls of introduced herbivores and weeds. This monitoring program did not measure variation across sites or sampling periods in the abundance of predators (feral cats and dingoes *Canis familiaris*), disease or introduced herbivores. The toxic cane toad *Rhinella marinus* colonised the area between sampling events in ca. 2001 to 2003. There has been no vegetation loss in this study area, but some vegetation change in the area over recent decades has been associated with fire (Murphy *et al.* 2010; Russell-Smith *et al.* 2010) and with the feral water buffalo *Bubalus bubalis* (Werner 2014)

Some context to this monitoring program is provided by a slightly earlier study of the mammal fauna in part of the same area (Woinarski *et al.* 2001). That study involved a re-sampling in 1999 of two sets of intensively-sampled sites (one initially sampled over the period 1985-87 and one in 1989-1993) in the Kapalga area of Kakadu (Braithwaite and Muller 1997). The trapping regime was consistent between the 1999 re-sampling and baseline sampling of these sites, but differed from that adopted in the main monitoring program described above, such that abundance measures are not comparable between this Kapalga re-sampling and the later main Kakadu monitoring program.

There is little detailed information on the mammal assemblage prior to these 1980s studies, however general surveys in the 1970s reported qualitatively but probably substantially higher abundance of some species (notably brush-tailed rabbit-rat *Conilurus penicillatus*) (Calaby 1973). Four mammal species are presumed extirpated in Kakadu, with the most recent records from the study area of water mouse *Xeromys myoides* in 1903, golden bandicoot *Isoodon auratus* in 1967, golden-backed tree-rat *Mesembriomys macrurus* in 1969, and northern hopping-mouse *Notomys aquilo* known in the park only from subfossil deposits, but with a live specimen captured nearby in 1973 (Woinarski and Winderlich 2014).

2. South-western Australia

This study was conducted in the upper catchment of the Warren River (the Upper Warren region, the western half is known as Greater Kingston, the eastern half as Perup), 300 km south of Perth. This ca. 250,000 ha area includes more than 144,000 ha of publicly-managed forest (principally nature reserve, national park and state forest) surrounded by and interspersed with agricultural land. The topography is gently undulating; the main environments comprise eucalypt forests and woodlands (Burrows and Christensen 2002; Department of Environment and Conservation 2012).

Fire (McCaw *et al.* 2005), timber harvesting (Wayne *et al.* 2006) and the control of the introduced red fox *Vulpes vulpes* have been significant management activities in the region (Wayne *et al.* in review). Some forest areas have been infected with the introduced soil-borne plant pathogen *Phytophthora cinnamomi* and most of the publicly managed forests are managed to minimise its spread (Department of Environment and Conservation 2012).

The long-term average annual rainfall ranges from 650 mm in the north-east to 1000 mm in the south-west of the region. There has been a 20-30% reduction in the average annual rainfall since records began in the early 1900s. Seven of the driest ten years occurred in the last ca. 20 years (1994, 2004, 2006, 2010, 2012, 2014, and 2015).

For this study area, we collate information for different sets of species monitored using different sampling protocols. Monitoring of medium-sized mammals (including the brush-tailed bettong or woylie *Bettongia penicillata,* southern brown bandicoot *Isoodon obesulus,* common brush-tailed possum *Trichosurus vulpecula* and western quoll or chuditch *Dasyurus geoffroii*) was generally conducted at least annually from 1974 to 2014, principally by means of an array of wire cage trapping transects (associated with forest tracks) (Wayne *et al.* in review). The number of transects surveyed in a given year was variable, initially being the same one or two transects (1974-1990), then with the addition of another two transects in 1994, another four between 1998-2000 and another three in 2005 (Wayne *et al.* in review). The annual mean capture rate for each species was derived per site from the means for each session within a given year (i.e. equal statistical weight was assigned to each session within a year). Annual means across the region were derived from the mean across sites within a given year (i.e. equal statistical weight was assigned to each site).

For smaller mammals, monitoring includes data from a discrete control-impact study investigating the responses of fauna to timber harvesting in the Kingston state forest block (Morris *et al.* 2001; Wayne *et al.* 2001; Wayne *et al.* 2016). Sampling for this study spanned the period 1994 to 2009, and was based on 22 trapping grids involving a consistent array of cage, Elliott and pitfall traps. The monitoring results reported here combine data from control and impact sites (if these were not significantly different) or control sites only (Wayne *et al.* in review). There were marked differences among mammal species in their trappability using different trap types: following Wayne *et al.* (in review), we report capture rates here in relation to trap types that were most applicable to sampling individual species. Capture rates from cage and Elliott traps were combined to provide estimates of abundance for the brush-tailed phascogale *Phascogale tapoatafa*. Trap rates for *Sminthopsis* spp. (two species, Gilbert's dunnart *S. gilberti* and grey-bellied dunnart *S. fuliginosus,* which were not always reliably distinguished in the field) were based on the combined capture rates from Elliott and pitfall traps. Capture rates for the native bush rat *Rattus*

fuscipes and introduced black rat *Rattus rattus* were derived from captures in wire cages only; and capture rates for the introduced house mouse *Mus musculus* comprised results from Elliott traps only.

Spotlight surveys along three standardised transects in the greater Kingston area, undertaken from 1995 to 2014, were used to derive indices of abundance for the western ring-tailed possum *Pseudocheirus occidentalis* (Wayne *et al.* 2005), tammar wallaby *Notamacropus eugenii*, western brush wallaby *Notamacropus irma* and western grey kangaroo *Macropus fuliginosus*.

The incidence of three medium-sized introduced mammals (cat, rabbit *Oryctolagus cuniculus* and red fox) was monitored from 2006 to 2013, using six arrays of 25 sand plots across the region (Wayne *et al.* in review).

Anthropogenic factors considered potential threats to some mammal populations, such as habitat fragmentation, proximity to agriculture and road densities, have been related to the abundance of western ring-tailed possum (Wayne *et al.* 2006) and woylie (Yeatman 2015) within the region. A series of population comparison studies have investigated the possible causes of the recent declines of woylie within the region and elsewhere including staple food resources and diet (Zosky 2011), introduced predators (Marlow *et al.* 2015) and disease (Pacioni 2010; Botero *et al.* 2013; Thompson *et al.* 2014; Wayne *et al.* 2015).

There is little detailed information on the area's mammal fauna prior to the establishment of the monitoring programs reported here. The region is notable for its retention of many threatened mammal species that have undergone broad-scale and severe declines elsewhere (e.g. numbat *Myrmecobius fasciatus*, western ring-tailed possum, brush-tailed bettong and tammar wallaby), but some mammal species were locally extirpated (e.g. bilby *Macrotis lagotis* and burrowing bettong or boodie *Bettongia lesueur*) in the 20th century (Abbott 2001); Ian Wilson *pers. comm.*).

3. South-eastern Australia

This study was conducted in an area of approximately 10,000 ha in the Great Otway National Park in southern Victoria. Within the study area is the Anglesea Heath (7141 ha) which was, prior to the establishment of the park, leased for the purpose of brown coal extraction over an area of 400 ha (1961-2015). The Anglesea Heath is recognised for its biodiversity, and a Land Management Cooperative Agreement was established to protect those values (McMahon and Brighton, 2002). Vegetation communities comprise a diverse mosaic of eucalypt forests, woodlands and heathlands, interspersed with dense wet shrublands (Kentish 1983; Land Conservation Council Victoria 1985; Wark *et al.* 1987). Fire management has been undertaken in the region since 1983, currently by the Department of Environment and Primary Industries (2014), and regular baiting for fox control has occurred since 2005 and prior to

that on a less regular basis (Antos and Yuen 2014; Parks Vic 2009, 2010). Significant areas have been infected with *P. cinnamomi* (Wilson *et al*. 2003) however management to minimise its spread has been limited.

The monitoring projects in south-eastern Australia comprised a set of different components that included survey, assessment of habitat requirements and responses to some management factors, within a broader monitoring context. Sampling project components considered the impacts upon mammal assemblages of some potential threat factors, including reduced rainfall (Wilson et al. 2007; Magnusdottir et al. 2008; Sale et al. 2008), fragmentation (Wilson et al. 2001), fire (Wilson et al. 1990; Wilson 1991; Aberton 1996; Wilson 1996; Wilson et al. 2001) and vegetation degradation due to P. cinnamomi (Laidlaw and Wilson 2006; Annett 2008). Monitoring design did not consider variation across sites or sampling periods in the abundance of introduced predators (feral cats and foxes) or of mammal disease.

The mammal assemblage in the study area includes several species listed as threatened under Victorian or national legislation – swamp antechinus *Antechinus minimus maritimus*, New Holland mouse *Pseudomys novaehollandiae*, white-footed dunnart *Sminthopsis leucopus*, long-nosed potoroo *Potorous tridactylus* and southern brown bandicoot *Isoodon obesulus* (Kentish 1983; Wilson *et al.* 1986; Wilson *et al.* 1990; Aberton 1996; Laidlaw and Wilson 2006).

Detailed accounts of the study areas and monitoring protocols are presented elsewhere (Wilson *et al.* 1986; Wilson *et al.* 1990; Wilson 1991, 1996; Lock and Wilson 1999; Wilson *et al.* 2001; Laidlaw and Wilson 2006; Annett 2008; Magnusdottir *et al.* 2008; Sale *et al.* 2008), with subsequent updates summarised here. The long-term monitoring results collated in this paper derive from eight studies conducted between 1975 and 2015 (Table 1).

In all study components, mammal sampling was restricted to live-trapping (using consistent arrays of Elliott traps, over 3 to 4 night periods); and no monitoring was undertaken for larger (i.e. > ca. 1 kg) mammal species. The abundance measure used in this paper was the tally of individuals captured per 100 trap nights per trapping session at each site. Eleven mammal species were reported in the monitoring (Table 2). This tally includes all small and medium-sized mammals, but not large macropods, known to have been present at the study sites between 1975 and 2015 (Wilson and Garkaklis 2014, 2015,2016).

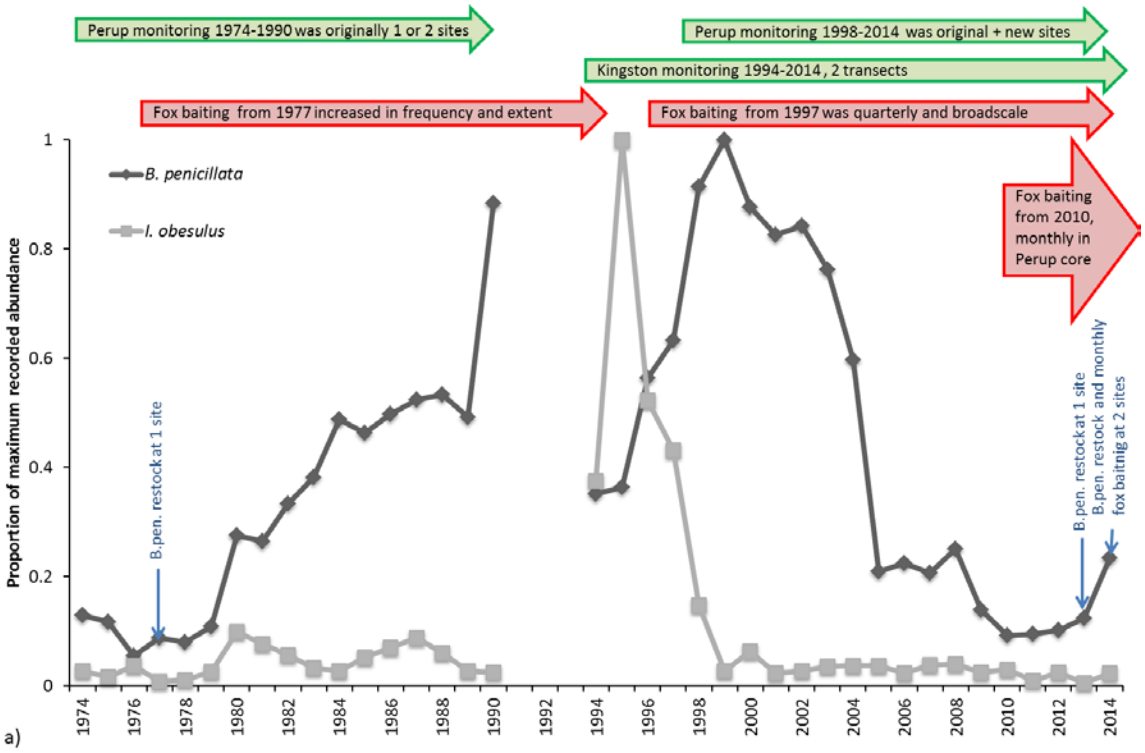
Table S1. Individual study site components and their monitoring periods for the south-eastern study area

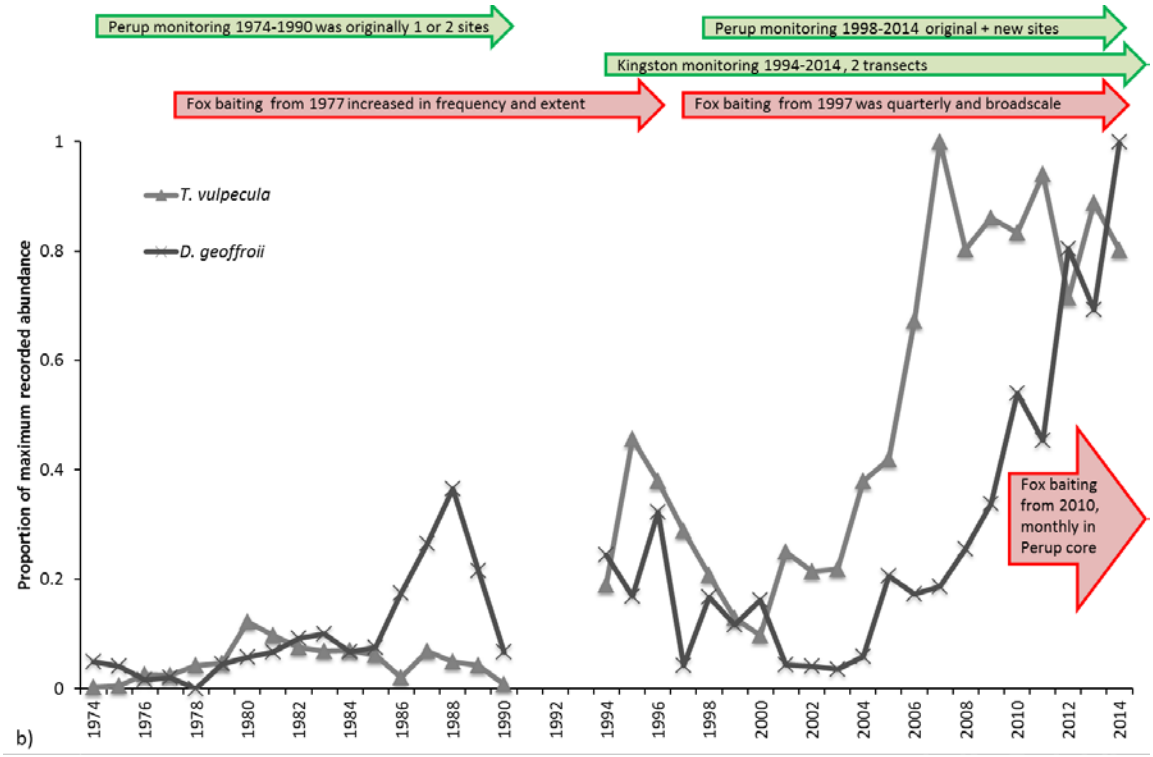
PF= Post Fire (monitored prior to and after 1983 Ash Wednesday Wildfire), with sites H=Harvey; R=Reserve; W=Woodland and S=Scrub

	PFH n=1	PFR n=1	PFW n= 5	PFS n = 5	Urquhart n=1	Flaxbourne n = 4	Bald Hills n = 1	Painkalac n= 1
Monitoring period (no. of sampling events)	1975-2015 (54)	1983-2015 (42)	1983-2014 (15)	1983-2015 (15)	1998-2014 (35)	1995-2015 (26)	1988-2015 (37)	1999-2015 (12)
Baseline years (trap-nights)	86-87 (600)	1986-87 (360)	1986-87 (600)	1986-87 (600)	2001 (300)	1995-96 (960)	2002 (600)	1999-2000 (180)
Final years (trap-nights)	2014-15 (195)	2013-15 (390)	2015 (450)	2015 (450)	2013-15 (235)	2013-15 (845)	2013-15 (900)	2015 (90)
Vegetation type	Heathy woodland	Heathy woodland	Heathy woodland	Coastal scrub	Heathy woodland	Heathy woodland	Heathy woodland	Estuarine woodland

Supplement 2: Longitudinal trends in mammal abundances at the (1) south-western and (2) south-eastern Australian study areas

Note that the relatively more straightforward (because they relate mostly to changes simply from a baseline sampling to a single subsequent sampling events) changes observed in the northern study area are not detailed here.




Perup monitoring 1974-1990 was originally 1 or 2 sites
Perup monitoring 1998-2014 original + new sites
Kingston monitoring 1994-2014, 2 transects
Fox baiting from 1977 increased in frequency and extent
Fox baiting from 1997 was quarterly and broadscale
T. vulpecula
D. geoffroii
Fox baiting from 2010, monthly in Perup core
Proportion of maximum recorded abundance
0
0.2
0.4
0.6
0.8
1
1974
1976
1978
1980
1982
1984
1986
1988
1990
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1994
1996
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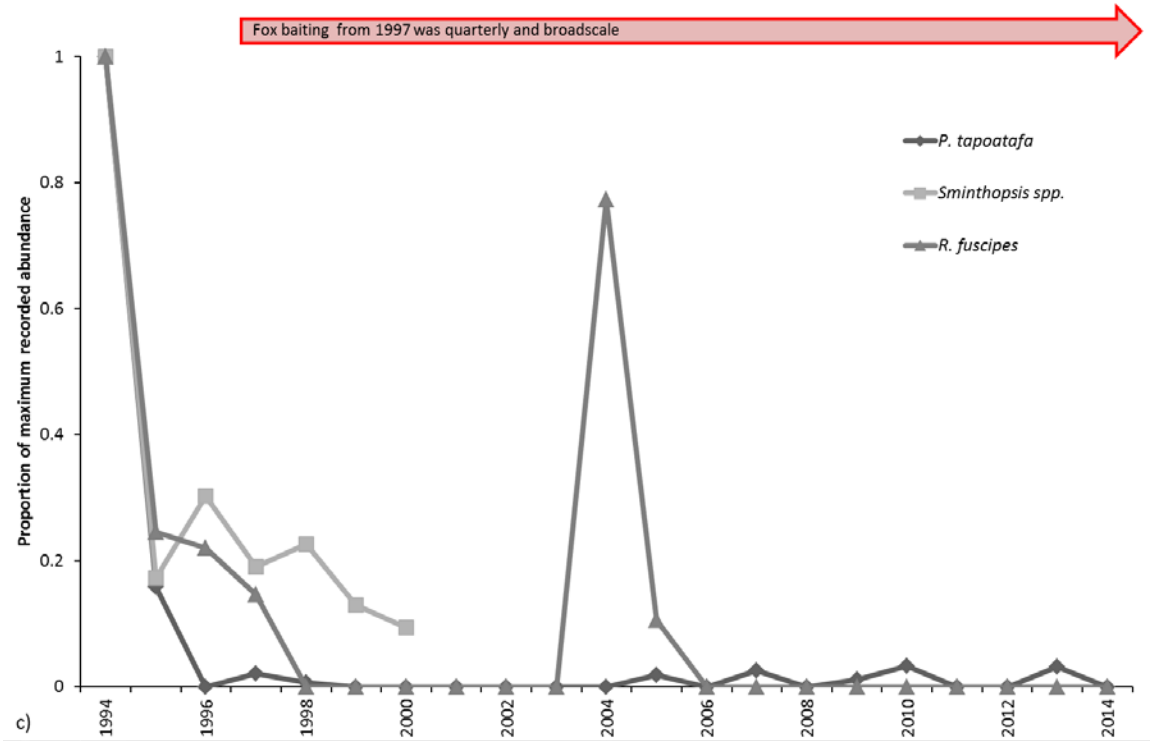
Fox baiting from 1997 was quarterly and broadscale
P. tapoatafa
Sminthopsis spp.
R. fuscipes
Proportion of maximum recorded abundance
0
0.2
0.4
0.6
0.8
1
1994
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2012
2014
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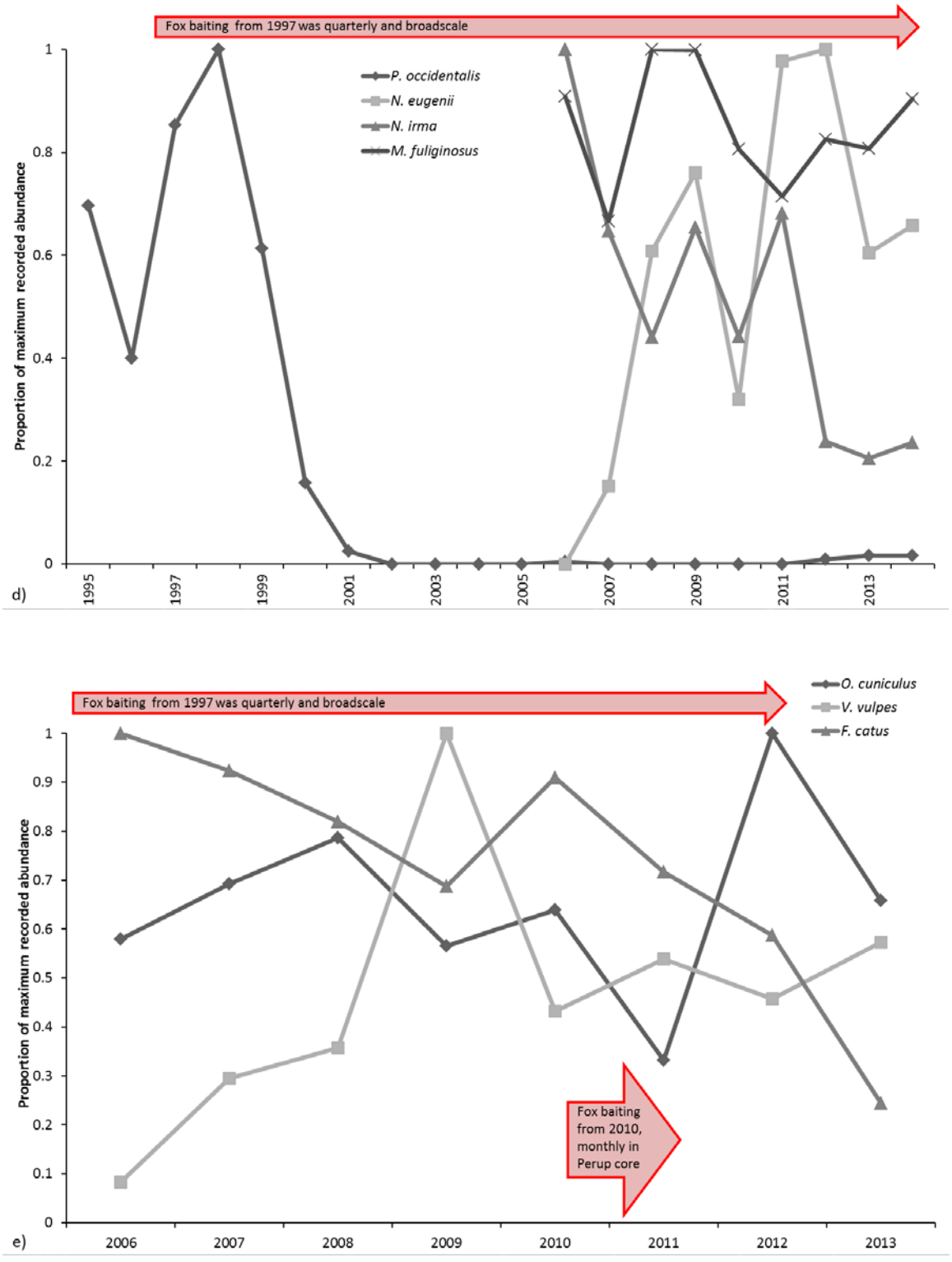
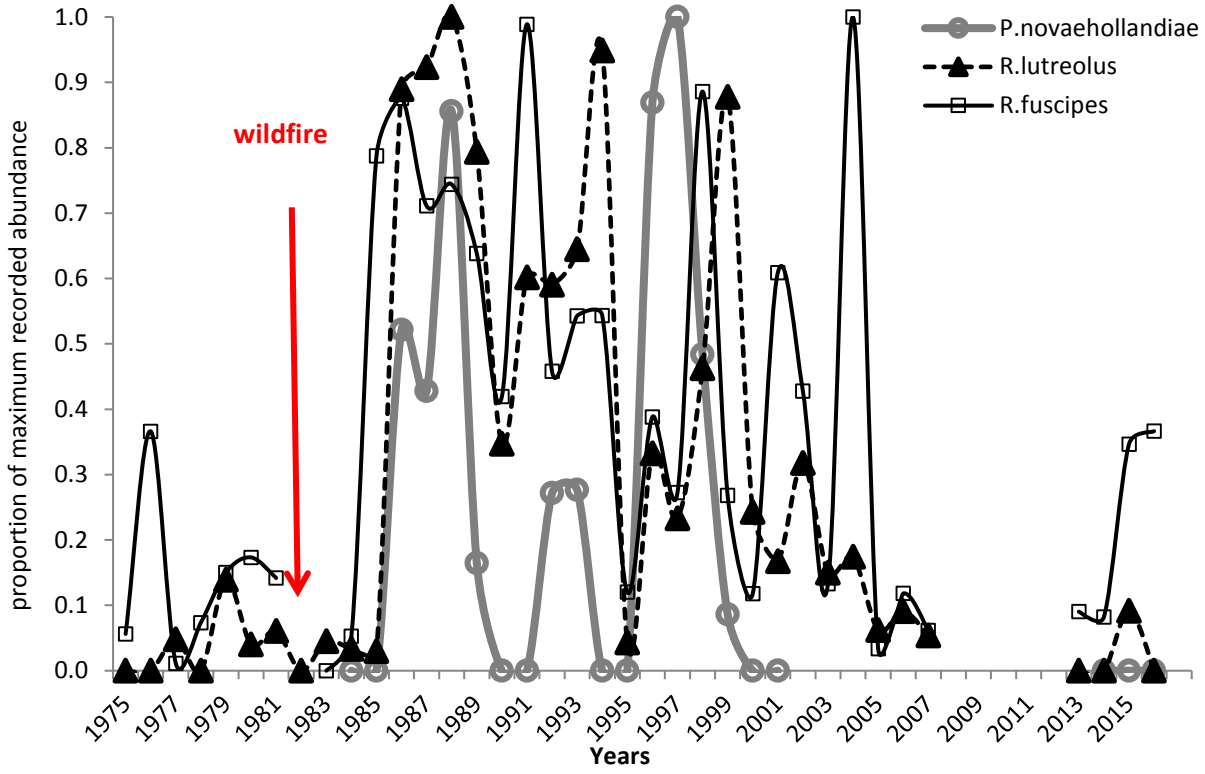


Fig. S1. Summary of changing abundance (expressed as the proportion of peak abundance) over the entire monitoring program for all species in all components of the south-western study area. (a) cage-trap transects (n=1-11

per year) – unsustained recovery; (b) cage-trap transects (n=1-11 per year) - recent increase; (c) cage, Elliott and pit trap grids (n=22); (d) spotlight transects (n=2-3); (e) sand-plot arrays (n=5-6).

a)



b)

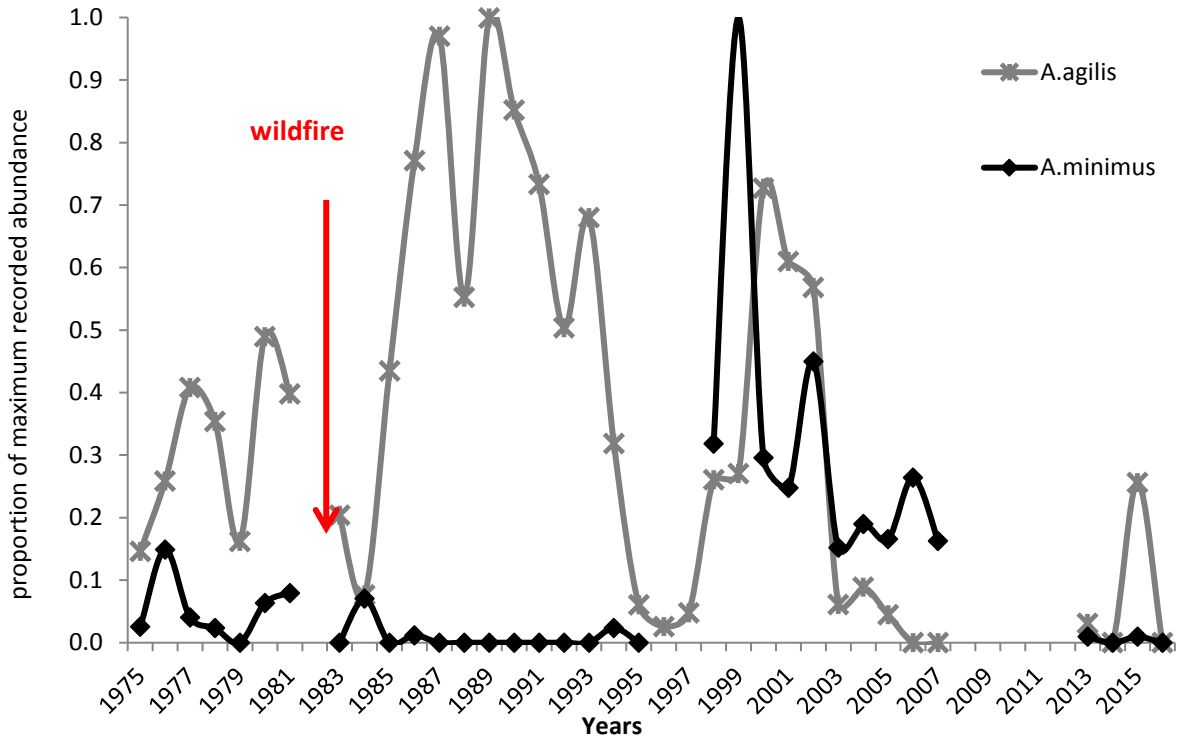


Fig. S2. Summary of changing abundance (expressed as the proportion of peak abundance) over the study programs for all species in all components of the south-eastern study area.

Table S2. Changes in abundance of mammal species for the south-eastern study. Values are the change in abundance (trap success rate) from baseline (first two years) to final two years

n= number of sites, PF = Post Fire (monitored prior to and after 1983 Ash Wednesday Wildfire), with sites H=Harvey; R=Reserve; W=Woodland and S=Scrub. x indicates that the species was not recorded in monitoring at this site

Heathy woodland Coastal scrub Estuarine wetland

	PFH n=1 1975-2015	PFR n=1 1983–15	PFW n= 5 1983 -14	PFS n = 5 1983-15	Urquhart n=1 1998 -14	Flaxbourne n = 4 1995 -15	BaldHills n = 1 1988-15	Painkalac n= 1 1999–15
A. agilis	-100%	0	no change	-100%	-100%	-100%	x	x
A. minimus	-100%	x	x	no change	-100%	x	-82%	-100%
S. leucopus	-100%	-100%	-100%	-100%	-100%	-100%	-100%	x
I. obesulus	-100%	x	-100%	no change	x	x	-100%	x
P. nasuta	x	x	x	x	x	x	x	x
C. nanus	-100%	x	x	x	x	-100%	+ observed	x
P. breviceps	-100%	x	x	x	x	x	x	x

P. tridactylus	-100%	x	x	x	x	x	x	x
P. novaehollandiae	x	-100%	x	x	x	-100%	x	x
R. fuscipes	-100%	-100%	-100%	no change	no change	-100%	no change	-100%
R. lutreolus	-100%	-100%	-100%	-78%	no change	-100%	- 100%	-50%
R. rattus	x	x	x	x	x	x	x	x
M. musculus	-100%	-100%	-100%	-93%	-100%	-100%	-100%	-78%
F. catus	x	x	x	x	x	x	x	x
O. cuniculus	x	x	x	x	x	x	x	x
V. vulpes	x	x	x	x	x	x	x	x

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