Wayne A. F., Wilson B. A., Woinarski J. C. Z. (2017) 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. *Wildlife Research* **44**, 114-126.

DOI: https://doi.org/10.1071/WR16178

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

A. F. Wayne[A,D], *B. A. Wilson*[B] *and J. C. Z. Woinarski*[C]

[A]Science and Conservation Division, Department of Parks and Wildlife, Locked Bag 2, Manjimup, WA 6258, Australia.

[B]School of Life and Environmental Sciences, Faculty of Science Engineering & Built Environment Deakin University, 221 Burwood Highway, Burwood, Melbourne, Vic. 3125, Australia.

[C]Threatened Species Recovery Hub of the National Environmental Science Program, Research Institute for the Environment and Livelihoods, Charles Darwin University, NT 0909, Australia.

[D]Corresponding author. Email: adrian.wayne@dpaw.wa.gov.au

Context. Since European settlement in 1788, much of the Australian terrestrial mammal fauna has declined or become extinct. The pattern of, and reason for, that decline was little documented, and is now difficult to decipher. Many mammal species are still declining, providing (an unfortunate) opportunity to better document the process, identify the causal factors and attempt to redress the problem.

Aim. We compare trends in mammal abundance reported in three recent longitudinal studies in conservation reserves in Australia. The studies were not established with the intention of documenting mammal decline, but marked simultaneous decline of co-existing species was the most striking feature of their results.

Methods. Long-term monitoring in Kakadu National Park, Northern Territory (2001–04 and 2007–09), the Upper Warren region of Western Australia (since 1974) and the Great Otway National Park, Victoria (since 1975) principally relied on trapping, but also some spotlighting and sand plots, to document changes and trends in abundance in their respective mammal assemblages.

Key results. Decline was reported in most mammal species, across taxonomic groups, diets and size classes, but mostly involved species <5500 g. The studies differed in their monitoring protocols and varied in the degree to which potential causal factors were monitored, thereby constraining interpretation of the drivers of declines. Inappropriate fire regimes and predation by feral cats are likely contributing factors in at least two study areas, and periods of markedly below-average rainfall are implicated in two areas.

Conclusions. We conclude the following: (1) conservation reserves in Australia may be failing to maintain at least some elements of the biodiversity that they were established to protect, and substantially enhanced management is required to redress this problem; (2) with current threats, mammal assemblages in Australia may be highly unstable; (3) substantial increase in effective long-term biodiversity monitoring programs in an adaptive management framework is needed; and (4) such monitoring programs will be more insightful if they also monitor factors driving population change.

Implications. Native mammal species declines and community disassembly may be occurring elsewhere. Long-term monitoring is critical for assessing trends in biodiversity and if done well, it can guide more effective and efficient management to deliver better conservation outcomes.

Additional keywords: conservation, extinction, fire, invasive alien species, management, predation.

Introduction

Globally, many plant and animal species are declining (Butchart *et al*. 2010). However, instances of simultaneous declines of many co-existing species are not often reported, at least not for continental areas and relatively intact environments. A high rate of decline in the Australian mammal fauna since European settlement in 1788 has included ~30 extinctions of endemic species (Johnson 2006; Woinarski *et al*. 2014, 2015). At least in southern and central Australia, much decline occurred before modern ecological studies, and the form and causes of that decline are difficult to retrospectively decipher (e.g. Abbott *et al*. 2014). With such extensive early loss, it may now be difficult to frame a baseline of what constitutes a 'normal' mammal assemblage in many areas (Bilney 2014).

The present-day Australian mammal fauna is now afforded a range of conservation management actions, such that there may be some grounds for assuming that the previous declining trends may now be stabilised or reversed. An extensive conservation reserve system, tallying ~17% of the nation (Taylor *et al*. 2014), provides protection of much biodiversity from acute threats such as habitat loss. Some potential threat factors (such as fire) are also actively managed in many reserves to benefit biodiversity. In many regions, notably in south-western Australia, there have been large-scale management programs extending over several decades focused on controlling a primary threat to declining mammals – predation by the introduced European red fox (*Vulpes vulpes*) (Wyre 2004; Marlow *et al*. 2015*b*). These programs have reported considerable successes, producing increases in the abundance of some native mammal species (Kinnear *et al*. 1988; Burrows and Christensen 2002; Morris *et al*. 2003; Wayne *et al*. 2011).

Some of this conservation management activity offers the opportunity to assess (more reliably than can be done for historic declines) the responses of mammal species to putative threatening factors and their management. However, biodiversity monitoring in Australia is limited and poorly coordinated (Lindenmayer *et al*. 2012; Lindenmayer *et al*. 2014). There are few long-term programs, little consistency in approach or purpose and little or no collation of data across individual monitoring programs, making it difficult to contextualise the results from any particular monitoring program. Furthermore, the limited number of, and inconsistency in monitoring programs, renders it very difficult to attempt any robust meta-analysis that may link observed trends across multiple sites to putative threats or their management.

In this paper, we consider results from three recent programs, widely spaced across Australia (Fig. 1), that monitor mammal assemblages (excluding bats). These three studies are among the few ongoing, substantial and long-lasting monitoring studies of mammal assemblages in mesic terrestrial environments (i.e. >600 mm mean annual rainfall) on mainland Australia, although we recognise that there have been some significant previous long-term monitoring studies of more restricted components of mammal assemblages (e.g. Heinsohn and Heinsohn (1999); Recher *et al*. (2009); Lindenmayer *et al*. (2011)).

The methodologies and results of the three case studies that we assemble here are each described in more detail in previous papers (Woinarski *et al.* 2010; Wilson and Garkaklis 2014, 2015; Wayne *et al.* 2017). Each of the studies was established for reasons other than documenting mammal decline. In our northern Australian study, monitoring was established initially to document vegetation responses to management that sought to improve fire regimes (Edwards *et al.* 2003); monitoring of mammals was added serendipitously to the vegetation monitoring program (Russell-Smith *et al.* 2014). In our south-western Australian study, some of the monitoring was established to assess biodiversity responses to putative threats (Morris *et al.* 2001; Wayne *et al.* 2005; Wayne *et al.* 2016) or to assess a predicted increase in the abundance of native mammals in response to intensive threat management (Orell 2004). In our south-eastern Australian study, the initial sampling was primarily for survey and study of the ecology of threatened species and small mammal communities (Kentish 1983; Wilson *et al.* 1986), followed by long-term studies of species and communities and their responses to threats (wildfire, fragmentation and habitat degradation due to the plant pathogen *Phytophthora cinnamomi*) (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).

Our objectives are to: (1) review the capabilities and shortcomings of these unrelated studies to document and interpret changing status and thus draw some recommendations for enhancing sensitivity and acuity of monitoring; (2) assess the extent of similarity in pattern and extent of trends in mammal species across these three areas; (3) consider whether the three studies may offer insight into causality (and hence management response) beyond that possible with a single study alone; and (4) consider whether any commonality in the trajectories we document may indicate a more general current trend for Australian mammals.

Materials and methods

Descriptions of the three study areas and monitoring programs

Key characteristics of the three study areas, and the studies themselves, are summarised in Table 1 and Supplement 1. Broadly, the northern Australian study sampled mammal assemblages at 136 sites in Kakadu National Park over two periods, 2001–04 and 2007–09, and we contextualise results from that primary study with comparable sampling in nearby Litchfield National Park, and with earlier studies in a part of Kakadu National Park. The south-western Australian study comprised a set of separate components (of variable duration and protocols, targeting different groups of mammal species) on publicly managed conservation estate in the Upper Warren region of Western Australia, extending from 1974 to the present. The south-eastern Australian study, in the Great Otway National Park, comprised a set of separate components (at different study sites and with varying sampling effort), extending discontinuously from 1975 to the present.

The three independent studies considered here are all in areas that have historically experienced comparatively low levels of mammal species declines (McKenzie *et al.* 2007) (Fig. 1).

Reporting changes in abundance

Measures of the abundance of individual mammal species reported here are based on trap success rates and, in some cases, tallies of individuals reported in standardised spotlight counts. In previous reporting of some study components, mark–recapture and other analyses have been used to derive more precise population density or the number of individuals known to be alive in the sampling area for some species (Wilson *et al*. 1986; Wilson *et al*. 1990; Wilson 1991; Lock and Wilson 1999; Wilson *et al*. 2001; Laidlaw and Wilson 2006; Magnusdottir *et al*. 2008; Wayne *et al*. 2013). However, the more precise population information cannot be calculated for most species in most study components, so we use trapping rate as a standard measure of abundance. Trap success rates generally provide a reasonable index of population size for individual species, but (because of varying trappability between species) do not provide a good indicator of relative population size between different species (Slade and Blair 2000; Hopkins and Kennedy 2004).

Monitoring in the three studies involved different numbers of sampling periods, protocols and measures of abundance. Statistical analyses for individual areas are described in more detail in previous publications (Woinarski *et al*. 2010; Wayne *et al*. 2017), with some summary information in Supplement 2. To simplify comparisons across the three studies, we categorise trends for species as either severe decline (>50% reduction in abundance), decline (20–50% reduction in abundance), stable (between 20% reduction and 20% increase), increase (20–50% increase), substantial increase (>50% increase) or uncertain (largely due to few records) over the course of the monitoring period. We note that this simple categorisation has some interpretational constraints, given that the three studies (or components of them) extend over different durations. In some cases where trends for individual species were inconsistent among different study components in a study area, our categorisation was based on the component with most substantial data. Our focus is mostly on trends over the course of the study period, but we note that, particularly in the south-eastern and south-western studies, there were some fluctuations in abundance (for at least some species in some periods in at least some sampling sites), associated mostly with episodes of disturbance (notably wildfire in the south-eastern study) and imposition of some management activities (such as reintroductions and predator control) in the south-western study. In such cases, we used overall trends across the entire monitoring period, or qualified our assessment of overall trend if there was a pronounced but non-linear pattern in the temporal variation. Differences in sampling design and other factors among these studies render it difficult to attempt robust statistical comparisons.

In describing results, we classify species by size class, as either very small (defined here as <35 g), small (35–500 g), medium (500–5500 g) or large (>5.5 kg). The thresholds for these size classes are mostly consistent with the 'critical weight range' (35–5500 g) recognised to be most susceptible to decline in Australian mammals (Burbidge and McKenzie 1989). Mammal nomenclature follows Jackson and Groves (2015).

Results

Northern Australia

There was a very marked decline in the abundance of most sampled very small, small and medium-sized mammal species over the main Kakadu monitoring program (2001–04 to 2007–09) (Table 2, Fig. 2,). This trend extended a decline reported from earlier (1985–87 to 1999 and 1989–93 to 1999) sampling of a small section of this study area (Braithwaite and Muller 1997; Woinarski *et al*. 2001). Declines were particularly pronounced for fawn antechinus (*Antechinus bellus*), northern quoll (*Dasyurus hallucatus*), northern brown bandicoot (*Isoodon macrourus*), common brush-tailed possum (*Trichosurus vulpecula*), black-footed tree-rat (*Mesembriomys gouldii*) and pale field-rat (*Rattus tunneyi*). In contrast, there was some increase for one species, the grassland melomys (*Melomys burtoni*). The brush-tailed rabbit-rat (*Conilurus penicillatus*) was probably extirpated in the study area over the course of this monitoring program (Woinarski and Winderlich 2014).

South-western Australia

The abundance of most mammal species changed markedly in this area over the course of the monitoring program (Table 2, Fig. 2; Supplement 2). The most conspicuous results were an increase and subsequent decline of three native species, decline of four species and a recent increase in three species.

During the late 1970s and 1980s, numbers of brush-tailed bettongs or woylies (*Bettongia penicillata*) increased steadily after a translocation within the region and the start of fox-baiting for fauna conservation in targeted areas in 1977 (Burrows and Christensen 2002). Most other native mammals were uncommon until fox control was greatly increased in frequency and extent between 1992 and 1996. However, after 1995 seven native mammal species declined severely and successively, with dunnarts (*Sminthopsis* spp.), bush rat (*Rattus fuscipes*) and brush-tailed phascogale (*Phascogale tapoatafa*) declining from 1995, southern brown bandicoot (*Isoodon obesulus*) from 1996, western ring-tailed possum (*Pseudocheirus occidentalis*) from 1999, brush-tailed bettong from 2000 and western brush wallaby (*Notamacropus irma*) from 2006 – this sequence correlates with increasing body size. The bush rat may now be extirpated in the study area, having not been recorded since 2005, notwithstanding ongoing sampling at sites that previously detected this species (Wayne *et al*. 2017). All other species that declined over this monitoring program have remained at low abundance, with none showing a substantial or sustained recovery.

Three native mammal species increased over the study period (Wayne *et al*. 2017) (Supplement 2): common brush-tailed possum since 2000, western quoll or chuditch (*Dasyurus geoffroii*) since 2003 and tammar wallaby (*Notamacropus eugenii*) since 2006, with the latter increase due mostly to translocations within the area. Western grey kangaroo (*Macropus fuliginosus*) was stable over the limited period in which it was monitored (2006–14). Of the five introduced mammal species present, two were reported insufficiently to assess trends (house mouse (*Mus musculus*) and black rat (*Rattus rattus*)). Feral cat (*Felis catus*) declined significantly between 2006 and 2013, red fox tended to increase over this period and rabbit (*Oryctolagus cuniculus*) was stable (Wayne *et al*. 2017).

South-eastern Australia

Most mammal species declined over the monitoring period, with very low abundance of almost all native mammal species, in the most recent sampling periods (Table 2, Fig. 2; Supplement 2).

Major declines were recorded in the 1990s and more severe declines followed in the period 2003–16. All sites trapped in 2013–16 had few native species present with 52% of sites having none, whereas in comparable early sampling three to nine native mammal species were recorded. The threatened New Holland mouse (*Pseudomys novaehollandiae*) disappeared from all sampling sites over this monitoring period, and may have been extirpated from this area. The threatened swamp antechinus (*Antechinus minimus*) was recorded in extremely low abundance in 2013–15 and was not recorded at sampling sites in 2016.

Although there was a general pattern of decline across most sites and species, some species fluctuated in abundance within the monitoring period, which was particularly associated with an extensive wildfire in 1983, that affected some sample sites. All native species declined at the 12 sites monitored in the 1–2 years after fire, followed by substantial recovery, with this recovery time and extent varying among species (Supplement 2). In contrast, the house mouse showed marked increase in the 1–2 years following fire, followed by decline.

A representative example is site PFH, for which 10 native mammal species were recorded before the 1983 wildfire (Supplement 2). Most species rapidly declined or disappeared after the wildfire, but some species (including agile antechinus (*A. agilis*), bush rat and swamp rat (*R. lutreolus*) recovered after 2–3 years, with abundance peaking 5–6 years post fire. In 1995 and 2002, only two species were recorded (bush rat, swamp rat), in low abundance, and in 2014 and 2015 no small mammals were captured in sampling at the site.

Trends across study areas

Unsurprisingly given the degree of geographic separation of the study areas, no single species was reported from all three areas (Table 2). Three native species were reported in sufficient numbers to detect trends at two areas: two of these species showed similar patterns of decline at both areas (southern brown bandicoot and bush rat in the south-eastern and south-western areas), but the third species (common brush-tailed possum) declined severely in the northern area but increased in the south-western area.

For native species with records sufficient to assign a trend (in Table 2), 67% showed some decline in the northern area, 64% in the south-western area and 90% in the south-eastern area. Most very small, small and medium-sized mammals declined in all three areas, but there was no prevailing trend for large species (in part because these were not adequately sampled in the northern and south-eastern studies) (Fig. 2*a*). Across all three areas, declines were evident in all of the most species-rich taxonomic groups, but especially for bandicoots, dasyurids and rodents (Fig. 2*b*). Declines occurred for species in all main dietary categories in all three areas, but especially so for omnivorous and granivorous species (Fig. 2*c*). The few species showing increase were relatively idiosyncratically scattered across size classes and taxonomic groups, but for dietary categories, were mostly herbivorous species.

Discussion

Comparison of monitoring programs

This comparison has illustrated some of the limitations in and differences between biodiversity monitoring programs in Australia. Notably, they are limited in spatial and temporal scale, and there is little standardisation in the methodology across programs, little coincident measurements of threats or management activity and limited ability to undertake rigorous analyses that may link trends to presumed threats or their management (Lindenmayer *et al*. 2012; Lindenmayer *et al*. 2014). For example, while the basic objectives of the three independent studies considered were broadly similar – essentially to monitor change in mammal assemblages over time – they focused on issues that were (at least initially) largely local or regional in scope and used markedly different methods.

The three monitoring programs were partly opportunistic in resourcing and implementation; there was relatively little long-term commitment to the ongoing maintenance of a consistent monitoring regime that could sufficiently address trends for the suite of native mammal species and their responses to management. Although all three programs included some consideration of the incidence and impacts of threats and management actions, this consideration was limited and variable across the three monitoring programs, and some putative key threats to the native mammal fauna were not explicitly sampled in all studies, with the most notable omission being sufficient sampling of introduced predators. Notably, the limited degree to which some threats were monitored constrains the interpretation of causes of the observed declines, and therefore the effectiveness of management responses. We recognise that causality may be demonstrated more acutely with well-designed experimentation (Frank *et al.* 2014; Leahy *et al.* 2015), but monitoring programs that incorporate consideration of variable treatments of threats and their management may also provide timely and compelling insight into causation.

These, (as well as other comparable) monitoring programs can be improved with the following: (1) increased consistency within monitoring programs in sampling over space and time (although we recognise that opportunism and flexibility in responses to funding availability and emerging issues is also desirable); (2) better coincident monitoring of threats and efficacy of management responses to threats; (3) integrated sampling across the full suite of the mammal assemblage; (4) a design that can identify defined decline points that would prompt management responses; and (5) a design that can be sufficiently powerful to detect gradual chronic trends and other trends in uncommon species. Greenville *et al.* (2016) provides a recent example of a monitoring program (for Australian arid zone mammals) and analytical pathway that incorporates many of these qualities. Applying some broadly adopted base standard to monitoring programs would also enable more robust comparisons across regions. We recognise that such enhancements are likely to increase costs of monitoring and may represent a formidable practical challenge, but this is likely to be justified if enhanced monitoring leads to more informed management, earlier warning of the need for remedial management and better conservation outcomes.

Characteristics and comparisons of trends in mammal assemblages

Although differing in degree, the prevailing trend in all three areas is of rapid and severe declines in most native mammal species. This has included probable extirpation (over a ~10–20 year period) of at least three species from sampled areas: the threatened brush-tailed rabbit-rat (northern area), the threatened New Holland mouse (south-eastern) and bush rat (south-western). Across species and study areas, there is also no indication of recovery, with the most recent sampling typically reporting the lowest abundance for at least some species.

In all three areas, the declines occurred in species across a range of taxonomic groups, sizes and diet. However, the declines occurred most markedly in some taxonomic groups (bandicoots, rodents, dasyurids), in some dietary categories (granivores and omnivores) and in all but the largest mammals. These results are broadly comparable with previous studies that have reviewed the susceptibility to decline in the Australian mammal fauna (McKenzie 1981; Burbidge and McKenzie 1989; Short and Smith 1994; McKenzie *et al.* 2007; Burbidge *et al.* 2008; Woinarski *et al.* 2015), indicating that this pattern of decline, and presumably the factors causing it, are continuing largely unabated. However, the declines in very small species (<35 g) and one large species (the western brush wallaby) observed in these studies also indicate susceptibility in some mammals in size-classes previously considered relatively resilient.

It may be inappropriate to consider any members of this mammal fauna secure, because most of these declines were a surprise to researchers and managers in these areas, and even abundant species were affected. This is a disconcerting result, from which we draw three lessons: (1) there is a need to undertake research on these species while it is most practicable (i.e. when they are abundant) to understand their ecologies and management requirements; (2) conservation management actions should focus on not only those species currently considered most threatened; and (3) monitoring programs should ensure they can provide an early warning of decline of species whether or not they are currently considered common and/or not at risk.

Contrary to the prevailing trend, there were a few native species that increased in abundance in the northern and south-western areas. This was most evident in the south-western area, where some increases were associated with intensive fox baiting and/or reintroductions. In some cases – notably for the brush-tailed bettong, western ring-tailed possum and southern brown bandicoot – these increases were short-lived, and were followed by severe declines – a phenomenon also observed elsewhere (N. Dexter, A. Wayne, J. Hone, R Duncan and M. Medina unpubl. data).

Comparisons among related species that show contrasting trends may provide insight into the factors driving these trends (Peery *et al*. 2004). There were a few potential cases of such matched species in these results. In the south-western study, tammar wallaby increased and western brush wallaby decreased, but there is insufficient knowledge of the ecology of these species to explain these different responses, and the monitoring period from which these trends were determined was brief (2006–14). In the northern Australian study, the grassland melomys increased but most other rodents decreased, but again the reasons for this contrast are unclear: this species may be a disturbance generalist (Begg *et al*. 1983), but such a rationale may be simply circular argument.

It remains to be seen whether the few species that have increased over the monitoring period, such as the common brush-tailed possum and western quoll in south-western Australia, can maintain their numbers or whether they too may subsequently decline; based on eventual declines of other abundant species, ongoing adequate monitoring would be prudent.

Causation

Conservation management for declining species is a formidable challenge, and may be especially so when there are many declining species in an area and many areas over which decline occurs. Three fundamental requirements of any conservation response to this challenge are: (1) a timely recognition there may be a problem; (2) confirmation that the declines are real; and (3) rigorously identifying (and thence ameliorating) the causal factor(s) (Caughley 1994). Having verified elsewhere that the observed declines are real (Woinarski *et al*. 2010; Wayne *et al*. 2013; Wilson and Garkaklis 2015; Wayne *et al*. 2017), a comparison of our results here does not reveal a clear common factor in these declines either within or among study areas, and multiple factors are probably involved (Table 3). In part, this lack of clarity is due to the limited extent to which the range of potential causal factors was sensitively monitored, both contemporaneously and in a manner complementary to the monitoring of mammal abundance.

Nonetheless, much of the observed declines is likely to be attributable to introduced predators (the feral cat in at least the northern and south-western areas and red fox in south-western and south-eastern areas) (Marlow *et al*. 2015*a*). In some cases, this predation impact is probably exacerbated by fire (Leahy *et al*. 2015), and fire itself may be a major factor causing changes in the mammal assemblages, at least in the northern (Woinarski *et al*. 2010; Lawes *et al*. 2015) and south-eastern areas (Wilson *et al*. 2001).

Previous accounts of some of these results indicate that drought and significant reductions in annual rainfall in the south-western (since the 1970s) and south-eastern (since the 1990s) study areas may be drivers for small mammal species declines (Rhind and Bradley 2002; Magnusdottir *et al*. 2008; Sale *et al*. 2008). Other less substantial possible contributing factors for at least some species in some areas may include disease, habitat fragmentation and (in the northern area alone) the introduced cane toad (*Rhinella marinus*). The considerable modification of vegetation associated with *P. cinnamomi* infestation has significant impacts on habitat utilisation and population dynamics of some small mammals (e.g. swamp antechinus, agile antechinus, swamp rat) in the south-eastern and south-western areas, with these species being less common in post-disease areas (Wilson *et al*. 1990; Laidlaw and Wilson 2006; Annett 2008). However, large parts of the south-western area that were not infected with *P. cinnamomi* still exhibited substantial declines. A part of the south-western area was subject to timber harvesting, and this activity may have had some limited affects for some species (Table 3). Of course, other factors not considered here may also be involved, but what is overwhelmingly clear is the very limited evidence and understanding of the drivers of mammal population changes, and the critical importance of resolving this for effective, efficient and reliable conservation management.

The declines of most species at our three study areas is of particular concern given that these areas were entirely or mostly in conservation reserves, in which many threats (notably habitat loss and hunting) that have affected mammal assemblages elsewhere in Australia and the world are excluded. Furthermore, all three areas have had some considered management aimed at the control of some putative threatening factors. The results reported here provide evidence that the conservation reserve system in Australia may be failing in its objective to maintain at least some components of the biodiversity it was established to protect. It is reasonable to presume that comparable or worse patterns would also be evident in much of the >80% of Australia that is not protected in conservation reserves, where threat mitigation efforts are less substantial or non-existent.

In contrast, there have been some remarkable recent cases of increase in many Australian mammal species in limited areas where introduced predators have been removed (Hayward *et al*. 2014), and at least one recent case of marked increases with effective broad-scale control of rabbits (Pedler *et al*. 2016). The contrast of native mammal trends in predator exclosures relative to trends reported in the three areas of this study exposed to conventional conservation management provides compelling evidence that introduced predators are a pivotal factor in the currently observed mammal declines. It also offers some hope that effective management of key threats may eventually allow sustained recovery of the declining mammal fauna, provided that these susceptible species have not disappeared before such management is implemented.

Temporal and spatial context

The mammal baselines in our study sites, as elsewhere in Australia, are not well established. Contemporary mammal faunas in much of Australia may be residual, and the abundances of many species may vary markedly from the historical (Bilney 2014). While there may be some anecdotal evidence for some species in these regions (e.g. south-west; Abbott 2006; Abbott *et al*. 2014), we generally cannot definitively state whether the monitoring period in these three studies coincided with the onset of decline or instead represent a continuation of a declining trend that was established before we started sampling. However, the three study areas are within bioregions previously considered to have been relatively little affected by mammal extinctions and declines (McKenzie *et al*. 2007).

It is difficult to assess the extent to which the patterns of decline observed in these three studies are representative of trends across Australia more broadly, because there are so few long-term monitoring programs for mammal assemblages elsewhere in Australia. A long-term monitoring program (based on spotlight surveys) in Tasmania indicates extensive decline for many species there, but provides no information on population trends for small mammal species (Driessen and Hocking 1992). A long-term monitoring program for arboreal mammals in forests of south-eastern Australia also provides evidence for generally declining trends, with acute declines for some species (Lindenmayer 2009). There are several important long-term monitoring programs for mammal assemblages in arid and semiarid Australia, but long-term population trends there are more difficult to discern from short-term fluctuations associated with marked variation in rainfall conditions (Dickman *et al*. 2014). A clear conclusion from the comparison of these three monitoring programs is that there is a need for more such programs in diverse environmental settings elsewhere in Australia.

Management responses and implications

These monitoring programs have been critical for providing information on the current status of many Australian native mammal species – in some cases, the only such trend information available. Ten species (fawn antechinus, northern quoll, northern brush-tailed phascogale (*Phascogale pirata*), western ring-tailed possum, brush-tailed bettong, brush-tailed rabbit-rat, black-footed tree-rat, New Holland mouse, swamp antechinus and Arnhem Land rock-rat (*Zyzomys maini*)) have been listed nationally as threatened (or uplisted) based in part on the evidence of decline reported in these monitoring programs, and this listing has provided impetus for some further research and directed management.

We recognise that managing multiple species, many of which are declining, in environments with many putative threats, and with finite resources, is a formidable challenge. The management response to the results from these monitoring programs has been limited, uneven and ineffective. Although the monitoring programs were variably linked to the relevant management agencies, the monitoring programs were largely without pre-defined trigger points that would prompt management responses, and were not strongly embedded in an adaptive management framework. However, in some cases, marked declines evident from these programs have led to some attempted remedial management responses, but even with the management refinements implemented in these study areas, it is clear that threat abatement activities have not managed to sustain a recovery or prevent substantial ongoing declines of most species. More consideration of assessment of threats in the monitoring design will improve these management programs, but targeted research is also required, especially given that it is likely that across the many species involved here, many threats have impacts and may be operating in complex interactions.

Conclusions

Long-term monitoring programs are vital for understanding the status of biodiversity. The three monitoring programs considered here, representing widely separated regions in Australia, provide substantial evidence of a mammal fauna characterised by rapid, severe and ongoing decline. Given these studies were largely in conservation reserves, it is likely that at least comparable levels of decline are occurring in unmonitored areas in many other parts of Australia.

Monitoring programs provide a critical evidence base for assessing trends in biodiversity, but they become particularly useful if they are embedded in a functional adaptive management context, can provide critical information on the factors causing population change and can measure the effectiveness of management response. Adequate and effective monitoring will remain a formidable challenge, especially in situations such as those exemplified by these three areas, where many disparate species are declining synchronously, probably because of a range of threatening factors operating in a potentially complex interactive manner. Nonetheless, conservation efforts are likely to continue to fail unless this challenge is met.

Supplementary material

A summary of the monitoring protocols for the three studies and trends in mammal abundances at areas in south-western Australia and south-eastern Australia are available from the Journal’s website.

Acknowledgements

The information presented here derives from long-term monitoring programs involving many researchers and supported by many agencies. For the north Australian study area, monitoring was undertaken by the Northern Territory Department of Natural Resources, Environment, the Arts and Sport (now Department of Land Resource Management), and we acknowledge support from Parks Australia and the Tropical Savannas Cooperative Research Centre. Field sampling involved many researchers but we acknowledge particularly Alaric Fisher and Kym Brennan and we thank Graeme Gillespie for providing preliminary results from recent monitoring.

For south-western Australia, monitoring was undertaken by the Western Australian Department of Parks and Wildlife and its predecessor agencies with some contributions by affiliated student projects. We acknowledge additional support from State and Federal Government funds in collaboration with the Warren Catchments Council, universities (most notably Murdoch University), Perth Zoo, the Australian Research Council, and World Wildlife Fund (WWF). Fieldwork involved many people including teams led by Neil Burrows, Per Christensen, Adrian Wayne and Ian Wilson. Many volunteers were also involved in the field work.

For the south-eastern study area, study components were undertaken by researchers at Deakin University (J. Aberton, K. Annett, M. Cullen, L. Gibson, A. Hanley, K. Hicks, M. Lock, R. Magnusdottir, D. Mills, W.S. Laidlaw, M. Sale and L. Zhuang-Griffin) and University of Western Australia (M. J. Garkaklis). We are grateful to the many people who provided field assistance. The work has been supported by Australian Research Council, Alcoa Australia, Holsworth Foundation, the Department of Conservation & Environment, Victoria, Deakin Foundation, Deakin University, M.A. Ingram Trust, the National Estate Grants Program and Parks Victoria. Scientific permits were issued by the Department of Natural Resources and Environment, Victoria and the Department of Sustainability and Environment Victoria, and ethics approvals by the Deakin University Animal Ethics Committee.

References

<jrn>Abbott, I. (2006). Mammalian faunal collapse in Western Australia, 1875–1925: the hypothesised role of epizootic disease and a conceptual model of its origin, introduction, transmission, and spread. *Australian Zoologist* **33**, 530–561. doi:10.7882/AZ.2006.024</jrn>

<edb>Abbott, I., Peacock, D., and Short, J. (2014). The new guard: the arrival and impacts of cats and foxes. In 'Carnivores of Australia: Past, Present and Future'. (Eds A. Glen and C. Dickman.) pp. 69–104. (CSIRO Publishing: Melbourne.)</edb>

<bok>Annett, K. (2008). Impacts of the plant pathogen *P. cinnamomi* (cinnamon fungus) on fauna and ecosystem functions. Ph.D. Thesis, Deakin University, Geelong.</bok>

<jrn>Begg, R. J., Walsh, B., Woerle, F., and King, S. (1983). Ecology of *Melomys burtoni*, the grassland melomys (Rodentia: Muridae) at Cobourg Peninsula, N.T. *Australian Wildlife Research* **10**, 259–267. doi:10.1071/WR9830259</jrn>

<jrn>Bilney, R. J. (2014). Poor historical data drive conservation complacency: the case of mammal decline in south-eastern Australian forests. *Austral Ecology* **39**, 875–886. doi:10.1111/aec.12145</jrn>

<jrn>Botero, A., Thompson, C. K., Peacock, C. S., Clode, P. L., Nicholls, P. K., Wayne, A. F., Lymbery, A. J., and Thompson, R. C. A. (2013). Trypanosomes genetic diversity, polyparasitism and the population decline of the critically endangered Australian marsupial, the brush tailed bettong or woylie (*Bettongia penicillata*). *International Journal for Parasitology. Parasites and Wildlife* **2**, 77–89. doi:10.1016/j.ijppaw.2013.03.001</jrn>

<jrn>Braithwaite, R. W., and Griffiths, A. D. (1994). Demographic variation and range contraction in the northern quoll, *Dasyurus hallucatus* (Marsupialia: Dasyuridae). *Wildlife Research* **21**, 203–217. doi:10.1071/WR9940203</jrn>

<jrn>Braithwaite, R. W., and Muller, W. J. (1997). Rainfall, groundwater and refuges: predicting extinctions of Australian tropical mammal species. *Australian Journal of Ecology* **22**, 57–67. doi:10.1111/j.1442-9993.1997.tb00641.x</jrn>

<jrn>Burbidge, A. A., and McKenzie, N. L. (1989). Patterns in the modern decline of Western Australia's vertebrate fauna: causes and conservation implications. *Biological Conservation* **50**, 143–198. doi:10.1016/0006-3207(89)90009-8</jrn>

<jrn>Burbidge, A. A., McKenzie, N. L., Brennan, K. E. C., Woinarski, J. C. Z., Dickman, C. R., Baynes, A., Gordon, G., Menkhorst, P. W., and Robinson, A. C. (2008). Conservation status and biogeography of Australia's terrestrial mammals. *Australian Journal of Zoology* **56**, 411–422. doi:10.1071/ZO08027</jrn>

<jrn>Burrows, N. D., and Christensen, P. E. S. (2002). Long-term trends in native mammal capture rates in a jarrah forest in south-western Australia. *Australian Forestry* **65**, 211–219. doi:10.1080/00049158.2002.10674872</jrn>

<jrn>Butchart, S. H. M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J. P. W., Almond, R. E. A., Baillie, J. E. M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K. E., Carr, G. M., Chanson, J., Chenery, A.

M., Csirke, J., Davidson, N. C., Dentener, F., Foster, M., Galli, A., Galloway, J. N., Genovesi, P., Gregory, R. D., Hockings, M., Kapos, V., Lamarque, J.-F., Leverington, F., Loh, J., McGeoch, M. A., McRae, L., Minasyan, A., Morcillo, M. H., Oldfield, T. E. E., Pauly, D., Quader, S., Revenga, C., Sauer, J. R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S. N., Symes, A., Tierney, M., Tyrrell, T. D., Vié, J.-C., and Watson, R. (2010). Global biodiversity: indicators of recent declines. *Science* **328**, 1164–1168. doi:10.1126/science.1187512</jrn>

<jrn>Caughley, G. (1994). Directions in conservation biology. *Journal of Animal Ecology* **63**, 215–244. doi:10.2307/5542</jrn>

<jrn>Dexter, N., and Murray, A. (2009). The impact of fox control on the relative abundance of forest mammals in East Gippsland, Victoria. *Wildlife Research* **36**, 252–261. doi:10.1071/WR08135</jrn>

<edb>Dickman, C. R., Wardle, G. M., Foulkes, J. N., and de Preu, N. (2014). Desert complex environments. In ‘Biodiversity and Environmental Change’. (Eds D. Lindenmayer, E. Burns, N. Thurgate and A. Lowe.) pp. 379–438. (CSIRO Publishing: Melbourne.)</edb>

<bok>Driessen, M. M., and Hocking, G. J. (1992). ‘Review and Analysis of Spotlight Surveys in Tasmania 1975–1990.’ (Department of Parks, Wildlife and Heritage: Hobart.)</bok>

<jrn>Edwards, A., Kennett, R., Price, O., Russell-Smith, J., Spiers, G., and Woinarski, J. (2003). Monitoring the impacts of fire regimes on vegetation in northern Australia: an example from Kakadu National Park. *International Journal of Wildland Fire* **12**, 427–440. doi:10.1071/WF03031</jrn>

<jrn>Frank, A., Johnson, C., Potts, J., Fisher, A., Lawes, M., Woinarski, J., Tuft, K., Radford, I., Gordon, I., Collis, M.-A., and Legge, S. (2014). Experimental evidence that feral cats cause local extirpation of small mammals in Australia’s tropical savanna. *Journal of Applied Ecology* **51**, 1486–1493. doi:10.1111/1365-2664.12323</jrn>

<jrn>Greenville, A. C., Wardle, G. M., Nguyen, V., and Dickman, C. R. (2016). Population dynamics of desert mammals: similarities and contrasts within a multispecies assemblage. *Ecosphere* **7**, e01343. doi:10.1002/ecs2.1343</jrn>

<jrn>Griffiths, A. D., Garnett, S. T., and Brook, B. W. (2015). Fire frequency matters more than fire size: testing the pyrodiversity–biodiversity paradigm for at-risk small mammals in an Australian tropical savanna. *Biological Conservation* **186**, 337–346. doi:10.1016/j.biocon.2015.03.021</jrn>

<edb>Hayward, M. W., Moseby, K., and Read, J. L. (2014). The role of predator exclosures in the conservation of Australian fauna. In ‘Carnivores of Australia: Past, Present and Future’. (Eds A. S. Glen and C. R. Dickman.) pp. 355–371. (CSIRO Publishing: Melbourne.)</edb>

<jrn>Heinsohn, G., and Heinsohn, R. (1999). Long-term dynamics of a rodent community in an Australian tropical rainforest. *Wildlife Research* **26**, 187–198. doi:10.1071/WR98020</jrn>

<jrn>Hopkins, H. L., and Kennedy, M. L. (2004). An assessment of indices of relative and absolute abundance for monitoring populations of small mammals. *Wildlife Society Bulletin* **32**, 1289–1296. doi:10.2193/0091-7648(2004)032[1289:AAOIOR]2.0.CO;2</jrn>

<bok>Jackson, S., and Groves, C. (2015). 'Taxonomy of Australian Mammals.' (CSIRO Publishing: Melbourne.)</bok>

<bok>Johnson, C. (2006). 'Australia's Mammal Extinctions: a 50000 Year History.' (Cambridge University Press: Melbourne.)</bok>

<ths>Kentish, K. M. (1983). Mine rehabilitation: a study of revegetation and fauna return at Anglesea, Victoria (1980–82). Masters Thesis, Deakin University, Geelong.</ths>

<jrn>Kinnear, J. E., Onus, M. L., and Bromilow, R. N. (1988). Fox control and rock-wallaby population dynamics. *Australian Wildlife Research* **15**, 435–450. doi:10.1071/WR9880435</jrn>

<jrn>Kinnear, J., Sumner, N. R., and Onus, M. L. (2002). The red fox in Australia – an exotic predator turned biocontrol agent. *Biological Conservation* **108**, 335–359. doi:10.1016/S0006-3207(02)00116-7</jrn>

<jrn>Laidlaw, W. S., and Wilson, B. A. (2006). Habitat utilisation by small mammals in a coastal heathland exhibiting symptoms of *Phytophthora cinnamomi* infestation. *Wildlife Research* **33**, 639–649. doi:10.1071/WR05080</jrn>

<jrn>Lawes, M. J., Murphy, B. P., Fisher, A., Woinarski, J. C. Z., Edwards, A., and Russell-Smith, J. (2015). Small mammals decline with increasing fire extent in northern Australia: evidence from long-term monitoring in Kakadu National Park. *International Journal of Wildland Fire* **24**, 712–722. doi:10.1071/WF14163</jrn>

<jrn>Leahy, L., Legge, S. M., Tuft, K., McGregor, H., Barmuta, L., Jones, M. E., and Johnson, C. N. (2015). Amplified predation after fire suppresses rodent populations in Australia's tropical savannas. *Wildlife Research* **42**, 705–716. doi:10.1071/WR15011</jrn>

<bok>Lindenmayer, D. (2009). 'Forest Pattern and Ecological Process: a Synthesis of 25 Years of Research.' (CSIRO Publishing: Melbourne.)</bok>

<jrn>Lindenmayer, D. B., Wood, J. T., McBurney, L., Michael, D., Crane, M., MacGregor, C., Montague-Drake, R., Gibbons, P., and Banks, S. C. (2011). Cross-sectional versus longitudinal research: a case study of trees with hollows and marsupials in Australian forests. *Ecological Monographs* **81**, 557–580. doi:10.1890/11-0279.1</jrn>

<jrn>Lindenmayer, D. B., Gibbons, P., Bourke, M., Burgman, M., Dickman, C. R., Ferrier, S., Fitzsimons, J., Freudenberger, D., Garnett, S. T., Groves, C., Hobbs, R. J., Kingsford, R. T., Krebs, C., Legge, S., Lowe, A. J., McLean, R., Montambault, J., Possingham, H., Radford, J., Robinson, D., Smallbone, L., Thomas, D., Varcoe, T., Vardon, M., Wardle, G., Woinarski, J., and Zerger, A. (2012). Improving biodiversity monitoring. *Austral Ecology* **37**, 285–294. doi:10.1111/j.1442-9993.2011.02314.x</jrn>

<edb>Lindenmayer, D., Burns, E., Thurgate, N., and Lowe, A. (Eds) (2014). 'Biodiversity and Environmental Change: Monitoring, Challenges and Direction.' (CSIRO Publishing: Melbourne.)</edb>

<jrn>Lock, M., and Wilson, B. (1999). The distribution of New Holland Mouse *P. novaehollandiae* with respect to vegetation at Anglesea, Victoria. *Wildlife Research* **26**, 565–577. doi:10.1071/WR97050</jrn>

<jrn>Magnusdottir, R., Wilson, B. A., and Hersteinsson, P. (2008). Dispersal and the influence of rainfall on a population of swamp antechinus (*Antechinus minimus maritimus*) in the Eastern Otways, Victoria, Australia. *Wildlife Research* **35**, 446–454. doi:10.1071/WR06156</jrn>

<jrn>Marlow, M. J., Thomas, N. D., Williams, A. A. E., Macmahon, B., Lawson, J., Hitchen, Y., Angus, J., and Berry, O. (2015*a*). Cats (*Felis catus*) are more abundant and are the dominant predator of woylies (*Bettongia penicillata*) after sustained fox (*Vulpes vulpes*) control. *Australian Journal of Zoology* **63**, 18–27. doi:10.1071/ZO14024</jrn>

<jrn>Marlow, N. J., Thomas, N. D., Williams, A. A. E., Macmahon, B., Lawson, J., Hitchen, Y., Angus, J., and Berry, O. (2015*b*). Lethal 1080 baiting continues to reduce European Red Fox (*Vulpes vulpes*) abundance after more than 25 years of continuous use in south-west Western Australia. *Ecological Management & Restoration* **16**, 131–141. doi:10.1111/emr.12162</jrn>

<jrn>McKenzie, N. L. (1981). Mammals of the Phanerozoic south-west Kimberley, Western Australia: biogeography and recent changes. *Journal of Biogeography* **8**, 263–280. doi:10.2307/2844762</jrn>

<jrn>McKenzie, N. L., Burbidge, A. A., Baynes, A., Brereton, R. N., Dickman, C. R., Gordon, G., Gibson, L. A., Menkhorst, P. W., Robinson, A. C., Williams, M. R., and Woinarski, J. C. Z. (2007). Analysis of factors implicated in the recent decline of Australia’s mammal fauna. *Journal of Biogeography* **34**, 597–611. doi:10.1111/j.1365-2699.2006.01639.x</jrn>

<bok>Menkhorst, P., and Knight, F. (2001). ‘A Field Guide to the Mammals of Australia.’ (Oxford University Press: Melbourne.)</bok>

<edb>Morris, K., Johnson, B., Rooney, J., and Ward, C. (2001). The short-term impacts of timber harvesting and associated activities on the abundance of medium-sized mammals in the jarrah forest of Western Australia. In ‘Nature Conservation 5. Conservation in the Production Environments: Managing the Matrix’. (Eds J. L. Craig, N. Mitchell and D. A. Saunders.) pp. 60–70. (Surrey Beatty and Sons: Sydney.)</edb>

<edb>Morris, K., Johnson, B., Orell, P., Gaikhorst, G., Wayne, A., and Moro, D. (2003). Recovery of the threatened chuditch (*Dasyurus geoffroii*): a case study. In ‘Predators with Pouches: the Biology of Carnivorous Marsupials’. (Eds M. Jones, C. Dickman and M. Archer.) pp. 435–451. (CSIRO Publishing: Melbourne.)</edb>

<jrn>O’Donnell, S., Webb, J. K., and Shine, R. (2010). Conditioned taste aversion enhances the survival of an endangered predator imperiled by a toxic invader. *Journal of Applied Ecology* **47**, 558–565. doi:10.1111/j.1365-2664.2010.01802.x</jrn>

<jrn>Orell, P. (2004). Fauna monitoring and staff training: Western Shield review – February 2003. *Conservation Science Western Australia* **5**, 51–95.</jrn>

<bok>Pacioni, C. (2010). The population and epidemiological dynamics associated with recent decline of woylies (*Bettongia penicillata*) in Australia. Ph.D. Thesis, Murdoch University, Perth.</bok>

<jrn>Pedler, R. D., Brandle, R., Read, J. L., Southgate, R., Bird, P., and Moseby, K. E. (2016). Rabbit biocontrol and landscape-scale recovery of threatened desert mammals. *Conservation Biology* **30**, 774–782. doi:10.1111/cobi.12684</jrn>

<jrn>Peery, M. Z., Beissinger, S. R., Newman, S. H., Burkett, E. B., and Williams, T. D. (2004). Applying the declining population paradigm: diagnosing causes of poor reproduction in the marbled murrelet. *Conservation Biology* **18**, 1088–1098. doi:10.1111/j.1523-1739.2004.00134.x</jrn>

<jrn>Possingham, H. P., Jarman, P., and Kearns, A. J. (2004). Independent review of Western Shield – February 2003. *Conservation Science Western Australia* **5**, 2–11.</jrn>

<jrn>Recher, H. F., Lunney, D., and Matthews, A. (2009). Small mammal populations in a eucalypt forest affected by fire and drought. I. Long-term patterns in an era of climate change. *Wildlife Research* **36**, 143–158. doi:10.1071/WR08086</jrn>

<edb>Rhind, S. G. (2004). Direct impacts of logging and forest management on the brush-tailed phascogale *Phascogale tapoatafa* and other arboreal marsupials in jarrah forest of Western Australia. In ‘Conservation of Australia’s Forest Fauna’. (Ed. D. Lunney.) pp. 639–655. (Royal Zoological Society of New South Wales: Sydney.)</edb>

<jrn>Rhind, S. G., and Bradley, J. S. (2002). The effect of drought on body size, growth and abundance of wild brush-tailed phascogales (*Phascogale tapoatafa*) in south-western Australia. *Wildlife Research* **29**, 235–245. doi:10.1071/WR01014</jrn>

<edb>Russell-Smith, J., Edwards, A., Woinarski, J., Fisher, A., Murphy, B. P., Lawes, M., Crase, B., and Thurgate, N. (2014). North Australian tropical savannas: the three parks savanna fire-effects plot network. In ‘Biodiversity and Environmental Change: Monitoring, Challenges and Direction’. (Eds D. Lindenmayer, E. Burns, N. Thurgate and A. Lowe.) pp. 335–378. (CSIRO Publishing: Melbourne.)</edb>

<jrn>Sale, M.G., Wilson, B.A., Arnould, J.P.Y., 2008. Factors influencing population dynamics in island and mainland populations of the swamp antechinus (*Antechinus minimus*; Marsupialia). *Australian Journal of Zoology* 56, 187-194.

<jrn>Short, J., and Smith, A. (1994). Mammal decline and recovery in Australia. *Journal of Mammalogy* **75**, 288–297. doi:10.2307/1382547</jrn>

<jrn>Slade, N. A., and Blair, S. M. (2000). An empirical test of using counts of individuals captured as indices of population size. *Journal of Mammalogy* **81**, 1035–1045. doi:10.1644/1545-1542(2000)081<1035:AETOUC>2.0.CO;2</jrn>

<bok>Taylor, M. F., Fitzsimons, J. A., and Sattler, P. S. (2014). ‘Building Nature’s Safety Net 2014: a Decade of Protected Area Achievements in Australia.’ (WWF-Australia: Sydney.)</bok>

<other>Wayne AF, Wheeler IB, Ward CG, Rooney JF, Mellican A (2001). The impacts of timber harvesting and associated activities on the small terrestrial vertebrates of the jarrah forest: Kingston Project progress report. Department of Conservation and Land Management, Manjimup, WA.</other>

<jrn>Wayne, A. F., Cowling, A., Rooney, J. F., Ward, C. G., Wheeler, I. B., Lindenmayer, D. B., and Donnelly, C. F. (2005). Factors affecting the detection of possums by spotlighting in Western Australia. *Wildlife Research* **32**, 689–700. doi:10.1071/WR04089</jrn>

<jrn>Wayne, A. F., Cowling, A., Lindenmayer, D. B., Ward, C. G., Vellios, C. V., Donnelly, C. F., and Calver, M. C. (2006). The abundance of a threatened arboreal marsupial in relation to anthropogenic disturbances at local and landscape scales in Mediterranean-type forests in south-western Australia. *Biological Conservation* **127**, 463–476. doi:10.1016/j.biocon.2005.09.007</jrn>

<jrn>Wayne, A. F., Liddelow, G. L., and Williams, M. R. (2011). FORESTCHECK: terrestrial vertebrate associations with fox control and silviculture in jarrah (*Eucalyptus marginata*) forest. *Australian Forestry* **74**, 336–349. doi:10.1080/00049158.2011.10676377</jrn>

<jrn>Wayne, A. F., Maxwell, M., Ward, C., Vellios, C., Ward, B., Liddelow, G. L., Wilson, I., Wayne, J. C., and Williams, M. R. (2013). The importance of getting the numbers right: quantifying the rapid and substantial decline of an abundant marsupial, *Bettongia penicillata*. *Wildlife Research* **40**, 169–183. doi:10.1071/WR12115</jrn>

<jrn>Wayne, A. F., Maxwell, M. A., Ward, C. G., Vellios, C. V., Wilson, I., Wayne, J. C., and Williams, M. R. (2015). Sudden and rapid decline of the abundant marsupial *Bettongia penicillata* in Australia. *Oryx* **49**, 175–185. doi:10.1017/S0030605313000677</jrn>

<jrn>Wayne, A. F., Maxwell, M. A., Ward, C. G., Vellios, C. V., Williams, M. R., and Pollock, K. H. (2016). The responses of a critically endangered mycophagous marsupial (*Bettongia penicillata*) to timber harvesting in a native eucalypt forest. *Forest Ecology and Management* **363**, 190–199. doi:10.1016/j.foreco.2015.12.019</jrn>

<jrn>Wayne, A. F., Maxwell, M. A., Ward, C. G., Wayne, J. C., Vellios, C. V., and Wilson, I. (2017). Recoveries and cascading declines of native mammals associated with control of an introduced predator. *Journal of Mammalogy*, in press. 10.1093/jmammal/gyw237</jrn>

<jrn>Wilson, B. A. (1991). The ecology of *Pseudomys novaehollandiae* (Waterhouse 1843) in the Eastern Otway Ranges, Victoria. *Wildlife Research* **18**, 233–247. doi:10.1071/WR9910233</jrn>

<edb>Wilson, B. A. (1996). Fire effects on vertebrate fauna and implications for fuel reduction burning and management. In ‘Fire and Biodiversity: the Effects and Effectiveness of Fire Management’. (Anon Ed.) pp. 131–147. (Department of Environment Sport and Territories: Canberra.)</edb>

<bok>Wilson, B. A., and Garkaklis, M. J. (2014). Assessment of the current status and distribution of the endangered mammals New Holland mouse, *Pseudomys novaehollandiae* and the swamp antechinus *Antechinus minimus* in the eastern Otways, Victoria. Progress Report to Parks Victoria. Deakin University, Geelong.</bok>

<bok>Wilson, B. A., and Garkaklis, M. J. (2015). Assessment of the current status and distribution of the endangered mammals New Holland mouse, *Pseudomys novaehollandiae* and the swamp antechinus *Antechinus minimus* in the eastern Otways, Victoria. Progress Report to Parks Victoria. Deakin University, Geelong.</bok>

<jrn>Wilson, B. A., Bourne, A. R., and Jessop, R. E. (1986). Ecology of small mammals in coastal heathland at Anglesea, Victoria. *Australian Wildlife Research* **13**, 397–406. doi:10.1071/WR9860397</jrn>

<jrn>Wilson, B. A., Robertson, D., Moloney, D. J., Newell, G. R., and Laidlaw, S. (1990). Factors affecting small mammal distribution and abundance in the eastern Otway Ranges, Victoria. *Proceedings of the Ecological Society of Australia* **16**, 379–394.</jrn>

<jrn>Wilson, B. A., Aberton, J., and Reichl, T. (2001). Effects of fragmented habitat and fire on the distribution and ecology of the swamp antechinus (*Antechinus minimus maritimus*) in the Eastern Otways, Victoria. *Wildlife Research* **28**, 527–536. doi:10.1071/WR00016</jrn>

<bok>Wilson, B. A., Lock, M., and Magnusdottir, R. (2007). 'Impact of Rainfall on Native Mammal Populations in Southeastern Australia, Perth.' (eds G. Moss, R.McLellan, G. Wardell - Johnson: Perth, Australia.)</bok>

<bok>Woinarski, J. C. Z., and Winderlich, S. (2014). 'A Strategy for the Conservation of Threatened Species and Threatened Ecological Communities in Kakadu National Park, 2014–2024.' (North Australian Hub of the National Environmental Research Program, Darwin.)</bok>

<jrn>Woinarski, J. C. Z., Milne, D. J., and Wanganeen, G. (2001). Changes in mammal populations in relatively intact landscapes of Kakadu National Park, Northern Territory, Australia. *Austral Ecology* **26**, 360–370. doi:10.1046/j.1442-9993.2001.01121.x</jrn>

<jrn>Woinarski, J. C. Z., Armstrong, M., Brennan, K., Fisher, A., Griffiths, A. D., Hill, B., Milne, D. J., Palmer, C., Ward, S., Watson, M., Winderlich, S., and Young, S. (2010). Monitoring indicates rapid and severe decline of native small mammals in Kakadu National Park, northern Australia. *Wildlife Research* **37**, 116–126. doi:10.1071/WR09125</jrn>

<jrn>Woinarski, J. C. Z., Ward, S., Mahney, T., Bradley, J., Brennan, K., Ziembicki, M., and Fisher, A. (2011). The mammal fauna of the Sir Edward Pellew island group, Northern Territory, Australia: refuge and death-trap. *Wildlife Research* **38**, 307–322. doi:10.1071/WR10184</jrn>

<bok>Woinarski, J. C. Z., Burbidge, A. A., and Harrison, P. L. (2014) 'The Action Plan for Australian Mammals 2012.' (CSIRO Publishing: Melbourne.)</bok>

<jrn>Woinarski, J. C. Z., Burbidge, A. A., and Harrison, P. L. (2015). Ongoing unravelling of a continental fauna: decline and extinction of Australian mammals since European settlement. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 4531–4540. doi:10.1073/pnas.1417301112</jrn>

<jrn>Wyre, G. (2004). Management of the Western Shield program: Western Shield Review – February 2003. *Conservation Science Western Australia* **5**, 20–30.</jrn>

Manuscript received 30 September, accepted 4 February 2017

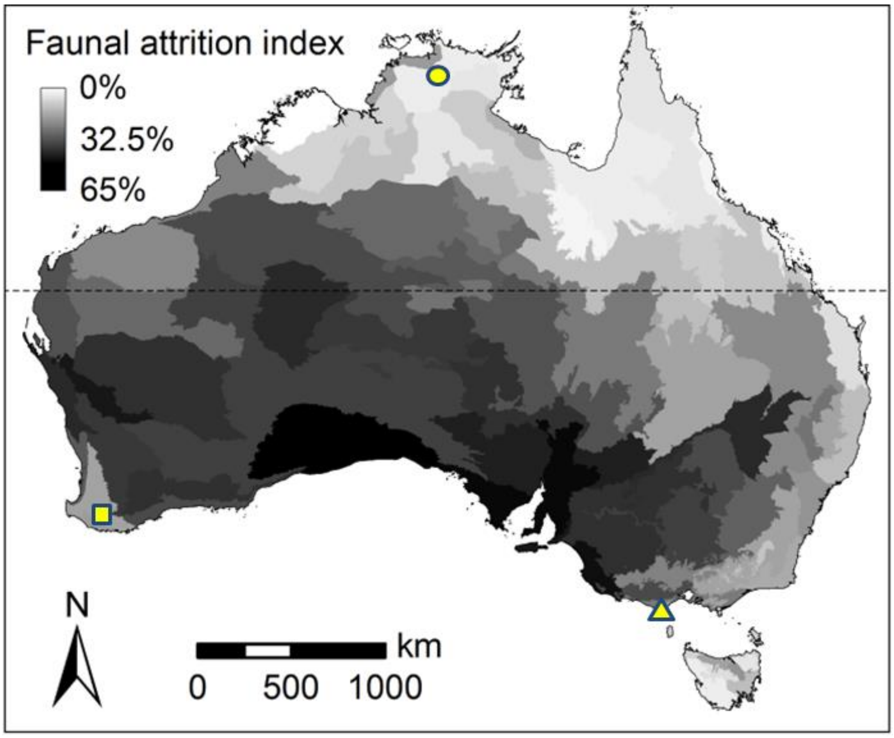


Fig. 1. Map of the study areas: northern Australia (circle), south-western Australia (square) and south-eastern Australia (triangle) in relation to the fauna attrition index (FAI) by McKenzie *et al*. (2007), whereby darker tones indicate bioregions with a higher proportion of mammal extinctions and/or declines.

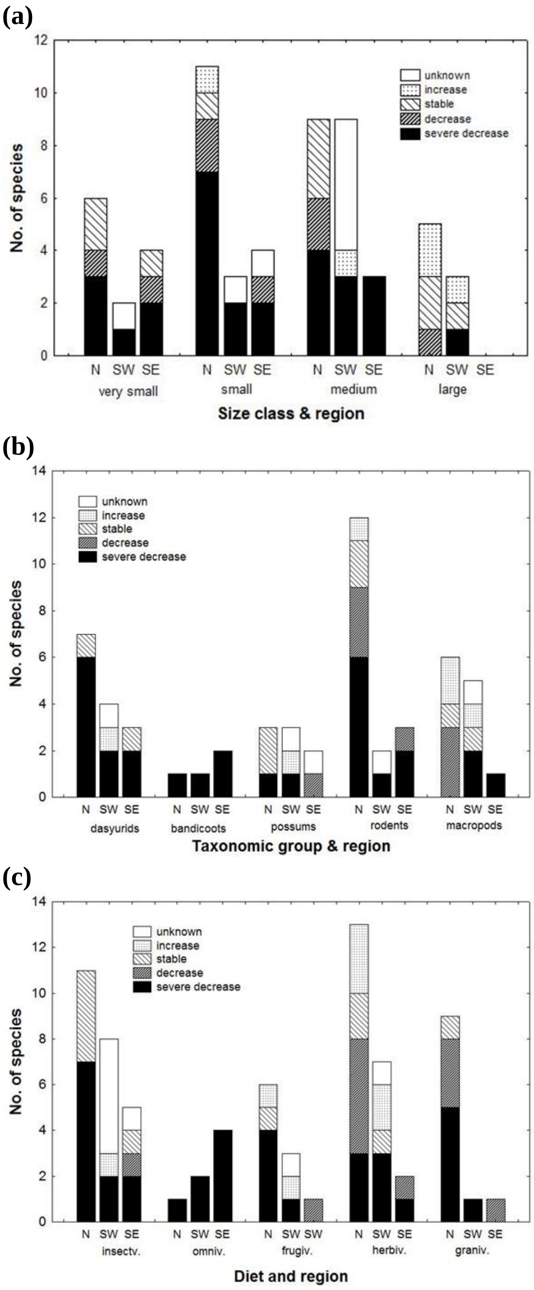


Fig. 2. Comparisons of status change across regions by (a) mammal size class, (b) taxonomic group and (c) diet. Trend status: severe decrease, >50% reduction in abundance over course of monitoring period; decrease, 20–50% reduction; stable, no marked trend; increase, >20% increase in abundance over monitoring period (including substantial (>50%) increase); and unknown, trend unclear. For size class: very small, <35 g, small, 35–500 g, medium, 500–5500 g; and large, >5500 g. For taxonomic group, only the more speciose groups are included: 'macropods' includes all families in suborder Macropodiformes, and 'possums' includes all families in suborder Phalangerida. For diet, a species may be included in more than one category and some minor dietary classes are omitted: insectv., insectivorous (but also includes some species with diet comprising some vertebrates); omniv., omnivorous; frugiv., frugivorous; herbiv., grass and foliage; and graniv., seeds.

Table 1. General characteristics of the three study areas and monitoring programs

Characteristic	Northern	South-western	South-eastern
Location	Kakadu National Park, with some related studies in a nearby reserve	Upper Warren region	Eastern Otway Ranges
Study area (km^2)	20 000	1400	100
Main tenure	Conservation reserve	Mix of conservation reserves and state forest	Conservation reserve
Main habitats	Tropical savannas and open woodlands, some wetlands, sandstone heathlands, rainforests	Eucalypt forests and woodlands	Eucalypt forests and woodlands, heathlands
Mean annual rainfall (mm)	900–1600, monsoonal seasonal	650–1000, Mediterranean seasonal	600–800, Mediterranean seasonal
Imposed management	Some fire management, limited control of large feral herbivores	Broadscale fox baiting, prescribed burning, timber harvesting (state forest only), Dieback (*P. cinnamomi*) disease risk management	Fire management, limited fox control and *P. cinnamomi* disease management
Management agency involvement in monitoring program	Agency established monitoring program, participated in some sampling, and reviewed results	Agency established monitoring program, undertook most sampling, and reviewed results	Agency provided some support for studies, but program was not closely integrated with studies
Extent of sampling period	2001–09, with some related earlier studies	1974–2014, but especially since 1994	1975–2015, but varying dates with different study components
Number of sample sites	136 plots, supplemented by information from similar but less extensive sampling in nearby areas	11 trapping transects (10 km each), 22 trapping grids, 3 spotlight transects (10 km), 6 sand plot arrays	19 trapping grids
Number of sampling events	2	Average 32 (7–80) trapping sessions per transect or grid; average 131 (123–138) spotlight surveys per transect; average 15 (6–20) sand plot surveys per array	12 to 54 repeat visits
Mammals sampled	All species, but limited information on larger species (> ~2 kg), and species not readily trappable (e.g. echidna)	All species, but limited information on larger species (> ~3 kg), and species not readily trappable (e.g. echidna and numbat)	Very small, small and medium-sized mammals only
No. of native mammal species recorded	31	15	11
No. of non-native mammals species recorded	6	5	4
Climate variation over sampling period	No marked variation from average	20–30% reduction in mean annual rainfall since 1970	Record rainfall deficits (1995, 1997–99, 2002–06, 2010–15)

Monitoring data on potential agents of population change	Vegetation, fire	Fire, timber harvesting (spatially limited), introduced predators (temporally limited)	Fire, vegetation, rainfall

Table 2. Mammal species recorded in the three studies and brief summary of changes in their status over the monitored period

Weights are taken as the mean value of ranges given in Menkhorst and Knight (2001). For ecological character: diet categories are C, meat; F, foliage and grass; G, seeds; I, invertebrates; M, fungi; N, nectar; O, omnivore; R, fruit (A, at least partly arboreal). For changes in status: SD, severe decrease (>50% reduction); D, decrease (20–50% reduction); 0, stable; I, increase; SI, substantial increase; ?, insufficient records so no trend assessment possible. Square brackets indicate few records, so trend assessment is of low reliability

Species	Weight (g)	Ecological character	Change in abundance over monitoring period		
			Northern	South-western	South-eastern
Monotremes					
Echidna, *Tachyglossus aculeatus*	4500	I	[0]	?	
Dasyurids					
[A]Fawn antechinus, *Antechinus bellus*	45	I:A	SD		
Agile antechinus, *Antechinus agilis*	30	I:A			0
Yellow footed antechinus, *Antechinus flavipes*	47	I:A		?	
[A]Swamp antechinus, *Antechinus minimus*	65	I			I then SD
[A]Northern quoll, *Dasyurus hallucatus*	650	CI:A	SD		
[A]Western quoll, *Dasyurus geoffroii*	1200	CI:A		SI (recent)	
[A]Northern brush-tailed phascogale, *Phascogale pirata*	210	CI:A	[SD]		
Brush-tailed phascogale, *Phascogale tapoatafa*	210	CI:A		SD	
Common planigale, *Planigale maculata*	9	I	SD		
Sandstone, pseudantechinus *Pseudantechinus bilarni*	26	CI	0		
Kakadu dunnart, *Sminthopsis butleri*	17	I	[SD]		
Red-cheeked dunnart, *Sminthopsis virginiae*	46	I	[SD]		
Gilbert's and grey-bellied dunnart, *Sminthopsis gilberti, S. fuliginosus*	20	I		SD	
White-footed dunnart, *Sminthopsis leucopus*	23	I			SD
Numbat					
[A]Numbat, *Myrmecobius fasciatus*	510	I		?	
Bandicoots					
Northern brown bandicoot, *Isoodon macrourus*	1375	O	SD		
[A]Southern brown bandicoot, *Isoodon obesulus*	850	O		I then SD	SD

Southern long-nosed bandicoot, *Perameles nasuta*	975	O			[SD]
Possums and gliders					
Eastern pygmy possum, *Cercartetus nanus*	26	NRI:A			[D]
Western pygmy possum, *Cercartetus concinnus*	13	NRI:A		?	
Common brushtail possum, *Trichosurus vulpecula*	2750	FNR:A	SD	SI (recent)	
Sugar glider, *Petaurus breviceps*	120	IN:A	[0]		?
Rock ring-tailed possum, *Petropseudes dahli*	1600	FNR:A	[0]		
[A]Western ring-tailed possum, *Pseudocheirus occidentalis*	920	FR: A		I then SD	
Potoroids and macropods					
Long-nosed potoroo, *Potorous tridactylus*	1130	O			[SD]
[A]Brush-tailed bettong, *Bettongia penicillata*	1300	M		I then SD	
Quokka, *Setonix brachyurus*	3300	F		?	
Wilkin's rock-wallaby, *Petrogale wilkinsi*	4000	F	D		
[A]Nabarlek, *Petrogale concinna*	1400	F	[D]		
Western grey kangaroo, *Macropus fuliginosus*	40 000	F		0	
Agile wallaby, *Notamacropus agilis*	21 000	F	I		
Tammar wallaby, *Notamacropus eugenii*	6000	F		I (recent)	
Western brush wallaby, *Notamacropus irma*	8000	F		SD	
Antilopine wallaroo, *Osphranter antilopinus*	35 000	F	[D]		
Black wallaroo, *Osphranter bernardus*	16 000	F	[0]		
Euro, *Osphranter robustus*	40 000	F	[I]		
Rodents					
[A]Brush-tailed rabbit-rat, *Conilurus penicillatus*	150	GF:A	[D]		
Water rat, *Hydromys chrysogaster*	910	CI	[0]	?	
Northern short-tailed mouse, *Leggadina lakedownensis*	20	G	[0]		
Grassland melomys, *Melomys burtonis*	75	FR:A	[I]		
[A]Black-footed tree-rat, *Mesembriomys gouldii*	740	IR:A	SD		
Kakadu pebble-mouse, *Pseudomys calabyi*	19	G	SD		
Delicate mouse, *Pseudomys delicatulus*	9	G	D		
Western chestnut mouse, *Pseudomys nanus*	37	GF	D		
[A]New Holland mouse, *Pseudomys novaehollandiae*	18	O			I then SD
Dusky rat, *Rattus colletti*	137	GF	SD		
Pale field-rat, *Rattus tunneyi*	130	GF	SD		
Bush rat, *Rattus fuscipes*	125	FGM		SD	I then D
Swamp rat, *Rattus lutreolus*	120	F			I then SD

Common rock-rat, *Zyzomys argurus*	55	GR	SD		
[A]Arnhem Land rock-rat, *Zyzomys maini*	125	GR	SD		
Dingo					
Dingo/dog, *Canis familiaris*	18 000	C	[0]		
Introduced species					
Black rat, *Rattus rattus*	197	O	[I]	[0]	?
House mouse, *Mus musculus*	18	O		[0]	I then SD?
Cat, *Felis catus*	4500	CI	[0]	SD	?
Rabbit, *Oryctolagus cuniculus*	1800	F		0	
Red fox, *Vulpes vulpes*	6000	CIR		[0]	?

[A]Listed as threatened under Australian legislation and/or by the IUCN.

Table 3. Summary of evidence for some possible causes of recent declines of mammals in the northern, south-western and south-eastern Australian study areas

NA, not applicable

Possible cause	Northern	South-western	South-eastern
Predation by introduced red fox	NA	Substantial evidence of at least temporary increases of some native mammals to fox control (Kinnear *et al*. 2002; Morris *et al*. 2003; Possingham *et al*. 2004)	No evidence in study area, but positive responses of some native mammals in nearby areas to fox control (Dexter and Murray 2009)
Predation by feral cat	No evidence in study area, but demonstrated population-level impacts for some native mammal species in nearby areas (Woinarski *et al*. 2011; Frank *et al*. 2014; Leahy *et al*. 2015)	Robust evidence especially for the brush-tailed bettong (Marlow *et al*. 2015*a*; Wayne *et al*. 2015)	No substantial evidence in study area for or against this factor
Fire	Fire frequency and intensity related to some mammal declines (Woinarski *et al*. 2010; Griffiths *et al*. 2015; Lawes *et al*. 2015) but did not fully explain all declines	No apparent association with the brush-tailed bettong or other species (A. Wayne, unpubl. data)	Seral responses to fire well established (Wilson 1996; Wilson *et al*. 2001)

Climate	No substantial change over monitoring period, or marked deviations from average	Drought impacts on brush-tailed phascogale (Rhind and Bradley 2002) but no recovery in subsequent wetter years (this study)	Periods of below-average rainfall drive reduced abundance of at least New Holland mouse and swamp antechinus (Wilson *et al*. 2007; Magnusdottir *et al*. 2008)
Disease	No relevant evidence, and no anecdotal support	May be a factor in the brush-tailed bettong decline (Pacioni 2010; Botero *et al*. 2013; Wayne *et al*. 2015)	No direct evidence for or against
Reduction in genetic diversity	No evidence in study area	Not for the brush-tailed bettong locally (Pacioni 2010)	No evidence in study area
Fragmentation	NA	Some impact on brush-tailed bettong genetics (Pacioni 2010)	Likely effect on New Holland mouse and swamp antechinus at some sample sites (Wilson *et al*. 2001)
Vegetation degradation due to *Phytophthora cinnamomi*	NA	Present but limited in extent within the study area where declines have been more pervasive	Associated with mammal declines at some sites (Wilson *et al*. 1990) but declines have been more pervasive
Other introduced species	Cane toad impacts on northern quoll (O'Donnell *et al*. 2010) but the species was already declining (Braithwaite and Griffiths 1994)	NA	NA
Timber harvesting	NA	Sensitive species include western ringtail possum (Wayne *et al*. 2001; Wayne *et al*. 2006) and brush-tailed phascogale (Rhind 2004) but not the brush-tailed bettong (Wayne *et al*. 2016); however, little of study area exposed to this factor	NA

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 1. 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

References

Abbott, I., 2001. The bilby *Macrotis lagotis* (Marsupialia: Peramelidae) in south-western Australia: original range limits, subsequent decline, and presumed regional extinction. *Records of the Western Australian Museum* 20, 271-306.

Aberton, J.G., 1996. Succession of small mammal communities after fire and reintroduction of the swamp antechinus *Antechinus minimus*. Ph.D. thesis, Deakin University, Geelong.

Annett, K., 2008. Impacts of the plant pathogen *P. cinnamomi* (Cinnamon fungus) on fauna and ecosystem functions. Ph.D. thesis, Deakin University, Geelong.

Antos, M.J., Yuen, K., 2014. Camera trap monitoring for inventory and management effectiveness in Victorian national parks: tailoring approaches to suit specific questions, in: Meek, P., Fleming, P. (Eds.), Camera trapping: wildlife management and research. Australian Wildlife Management Society, NSW, pp. 13-23.

Botero, A., Thompson, C.K., Peacock, C.S., Clode, P.L., Nicholls, P.K., Wayne, A.F., Lymbery, A.J., Thompson, R.C.A., 2013. Trypanosomes genetic diversity, polyparasitism and the population decline of the critically endangered Australian marsupial, the brush tailed bettong or woylie (*Bettongia penicillata*). *International Journal for Parasitology: Parasites and Wildlife* 2, 77-89.

Braithwaite, R.W., Muller, W.J., 1997. Rainfall, groundwater and refuges: predicting extinctions of Australian tropical mammal species. *Australian Journal of Ecology* 22, 57-67.

Burrows, N.D., Christensen, P.E.S., 2002. Long-term trends in native mammal capture rates in a jarrah forest in south-western Australia. *Australian Forestry* 65, 211-219.

Calaby, J.H., 1973. Mammals, in: Anon (Ed.), Alligator Rivers Region Environmental Fact-finding Study. CSIRO, Canberra.

Department of Environment and Conservation, 2012. Perup Management Plan 2012, Department of Environment and Conservation, Perth.

Department of Environment and Primary Industries, 2014. Strategic bushfire management plan Barwon Otway bushfire risk landscape, Victorian Government, Melbourne.

Edwards, A., Kennett, R., Price, O., Russell-Smith, J., Spiers, G., Woinarski, J., 2003. Monitoring the impacts of fire regimes on vegetation in northern Australia: an example from Kakadu National Park. *International Journal of Wildland Fire* 12, 427-440.

Kentish, K.M., 1983. Mine rehabilitation: a study of revegetation and fauna return at Anglesea, Victoria (1980-1982). M.Sc. thesis, Deakin University, Geelong.

Laidlaw, W.S., Wilson, B.A., 2006. Habitat utilisation by small mammals in a coastal heathland exhibiting symptoms of *Phytophthora cinnamomi* infestation. *Wildlife Research* 33, 639-649.

Land Conservation Council Victoria, 1985. Report on the Melbourne Area, District 1 review, Land Conservation Council, Melbourne.

Lock, M., 2005. Population ecology and captive breeding of *Pseudomys novaehollandiae* at Anglesea. Ph.D, thesis. Deakin University, Geelong.

Lock, M., Wilson, B., 1999. The distribution of New Holland Mouse (*Pseudomys novaehollandiae*) with respect to vegetation at Anglesea, Victoria. *Wildlife Research* 26, 565-577.

Magnusdottir, R., Wilson, B.A., Hersteinsson, P., 2008. Dispersal and the influence of rainfall on a population of swamp antechinus (*Antechinus minimus maritimus*) in the Eastern Otways, Victoria, Australia. *Wildlife Research* 35, 446-454.

Marlow, M.J., Thomas, N.D., Williams, A.A.E., Macmahon, B., Lawson, J., Hitchen, Y., Angus, J., Berry, O., 2015. Cats (*Felis catus*) are more abundant and are the dominant predator of woylies (*Bettongia penicillata*) after sustained fox (*Vulpes vulpes*) control. *Australian Journal of Zoology* 63, 18-27.

McCaw, L., Hamilton, T., Rumley, C., 2005. Application of fire history records to contemporary management issues in south-west Australian forests, in: Calver, M.C., Bigler-Cole, H., Bolton, G., Dargavel, J., Gaynor, A., Horwitz,P., Mills, J., Wardell-Johnson. G. (Eds.), 6th National Conference of the Australian Forest History Society Inc. Millpress Science Publishers, Rotterdam, pp. 555-564.

McMahon, K., Brighton, M., 2002. Anglesea Heath Management Plan November 2002, Parks Victoria and Alcoa World Alumina Australia

Morris, K., Johnson, B., Rooney, J., Ward, C., 2001. The short-term impacts of timber harvesting and associated activities on the abundance of medium-sized mammals in the jarrah forest of Western Australia, in: Craig, J.L., Mitchell, N., Saunders, D.A. (Eds.), Nature conservation 5. conservation in the production environments: managing the matrix. Surrey Beatty and Sons, Sydney, pp. 60-70.

Murphy, B.P., Cochrane, M.A., Russell-Smith, J., 2015. Prescribed burning protects endangered tropical heathlands of the Arnhem Plateau, northern Australia. *Journal of Applied Ecology* 52, 980-991.

Murphy, B.P., Russell-Smith, J., Prior, L.D., 2010. Frequent fires reduce tree growth in northern Australian savannas: implications for tree demography and carbon sequestration. *Global Change Biology* 16, 331-343.

Pacioni, C., 2010. The population and epidemiological dynamics associated with recent decline of woylies (*Bettongia penicillata*) in Australia. Ph.D. thesis, Murdoch University, Perth.

Parks Victoria, and DSE, 2009. Caring for Country — the Otways and you. Great Otway National Park and Otway Forest Park Management Plan, Parks Victoria and DSE, Melbourne.

Parks Victoria, 2010. Signs of Healthy Parks Ecological Monitoring Program, Parks Victoria, Melbourne.

Russell-Smith, J., Edwards, A., Woinarski, J., Fisher, A., Murphy, B.P., Lawes, M., Crase, B., Thurgate, N., 2014. North Australian tropical savannas: the three parks savanna fire-effects plot network, in: Lindenmayer, D., Burns, E., Thurgate, N., Lowe, A. (Eds.), Biodiversity and environmental change: monitoring, challenges and direction. CSIRO Publishing, Melbourne, pp. 335-378.

Russell-Smith, J., Edwards, A.C., Woinarski, J.C.Z., McCartney, J., Kerin, S., Winderlich, S., Murphy, B.P., Watt, F., 2009. Fire and biodiversity monitoring for conservation managers: a 10-year assessment of the 'Three Parks' (Kakadu, Litchfield and Nitmiluk) program, in: Russell-Smith, J., Whitehead, P.J., Cooke, P. (Eds.), Culture, ecology and economy of fire management in north Australian savannas: rekindling the *wurrk* tradition. CSIRO Publishing, Collingwood, pp. 257-286.

Russell-Smith, J., Price, O.F., Murphy, B.P., 2010. Managing the matrix: decadal responses of eucalypt-dominated savanna to ambient fire regimes. *Ecological Applications* 20, 1615-1632.

Sale, M.G., Wilson, B.A., Arnould, J.P.Y., 2008. Factors influencing population dynamics in island and mainland populations of the swamp antechinus (*Antechinus minimus*; Marsupialia). *Australian Journal of Zoology* 56, 187-194.

Thompson, C., Wayne, A., Godfrey, S., Thompson, R.C., 2014. Temporal and spatial dynamics of trypanosomes infecting the brush-tailed bettong (*Bettongia penicillata*): a cautionary note of disease-induced population decline. *Parasites & Vectors* 7, 169.

Wark, M.C., White, M.D., Robertson, D.J., Marriott, P.F., 1987. Regeneration of heath and heath woodland in the north-eastern otway ranges following the wildfire of February 1983. *Proceedings of the Royal Society of Victoria* 99, 51-88.

Wayne, A.F., Cowling, A., Lindenmayer, D.B., Ward, C.G., Vellios, C.V., Donnelly, C.F., Calver, M.C., 2006. The abundance of a threatened arboreal marsupial in relation to anthropogenic disturbances at local and landscape scales in Mediterranean-type forests in south-western Australia. *Biological Conservation* 127, 463-476.

Wayne, A.F., Cowling, A., Rooney, J.F., Ward, C.G., Wheeler, I.B., Lindenmayer, D.B., Donnelly, C.F., 2005. Factors affecting the detection of possums by spotlighting in Western Australia. *Wildlife Research* 32, 689-700.

Wayne, A.F., Maxwell, M.A., Ward, C.G., Vellios, C.V., Williams, M.R., Pollock, K.H.. 2016. The responses of a critically endangered mycophagous marsupial (*Bettongia penicillata*) to timber harvesting in a native eucalypt forest. *Forest Ecology and Management* 363, 190-199.

Wayne, A.F., Maxwell, M.A., Ward, C.G., Vellios, C.V., Wilson, I., Wayne, J.C., Williams, M.R., 2015 Sudden and rapid decline of the abundant marsupial *Bettongia penicillata* in Australia. *Oryx* 49, 175-185.
Wayne, A.F., Maxwell, M.A., Ward, C.G., Wayne, J.C., Vellios, C.V., Wilson, I., (in review). Recoveries and cascading declines of native mammals associated with control of an introduced predator. *Journal of Mammalogy*.
Wayne, A.F., Wheeler, I.B., Ward, C.G., Rooney, J.F., Mellican, A., 2001. The impacts of timber harvesting and associated activities on the small terrestrial vertebrates of the jarrah forest: Kingston Project progress report, Department of Conservation and Land Management, Manjimup.
Werner, P.A., 2014. The rise and fall of the Asian water buffalo in the monsoonal tropics of northern Australia, in: Prins, H.H.T., Gordon, I.J. (Eds.), Invasion biology and ecological theory: insights from a continent in transformation. Cambridge University Press, Cambridge, pp. 452-496.
Wilson, B.A., 1991. The ecology of *Pseudomys novaehollandiae* (Waterhouse 1843) in the Eastern Otway Ranges, Victoria. *Wildlife Research* 18, 233-247.
Wilson, B.A., 1996. Fire effects on vertebrate fauna and implications for fuel reduction burning and management, in: Anon (Ed.), Fire and Biodiversity: the effects and effectiveness of fire management. Department of Environment Sport and Territories, Canberra, pp. 131-147.
Wilson, B.A., Garkaklis, M.J., 2014. Assessment of the current status and distribution of the endangered mammals New Holland Mouse, *Pseudomys novaehollandiae* and the Swamp Antechinus *Antechinus minimus* in the eastern Otways, Victoria. Progress Report to Parks Victoria. Deakin University, Melbourne.
Wilson, B.A., Garkaklis, M.J. 2015. Assessment of the current status and distribution of the endangered mammals New Holland Mouse, *Pseudomys novaehollandiae* and the Swamp Antechinus *Antechinus minimus* in the eastern Otways, Victoria. Progress Report to Parks Victoria. Deakin University, Melbourne.
Wilson, B.A., Garkaklis, M.J., 2016. Assessment of the status and distribution of the endangered New Holland mouse and the Swamp antechinus in the eastern Otways: data for the Parks Victoria Decision Support System. Final Report to Parks Victoria. Deakin University, Melbourne.
Wilson, B.A., Aberton, J., Lewis, A., 2003. A spatial model for predicting the presence of cinnamon fungus (*Phytophthora cinnamomi*) in sclerophyll vegetation communities in south-eastern Australia. *Austral Ecology* 28, *108-115*.
Wilson, B.A., Aberton, J., Reichl, T., 2001. Effects of fragmented habitat and fire on the distribution and ecology of the Swamp Antechinus (*Antechinus minimus maritimus*) in the Eastern Otways, Victoria. *Wildlife Research* 28, 527-536.
Wilson, B.A., Bourne, A.R., Jessop, R.E., 1986. Ecology of small mammals in coastal heathland at Anglesea, Victoria. *Australian Wildlife Research* 13, 397-406.
Wilson, B.A., Lock, M., Magnusdottir, R., 2007. Impact of rainfall on native mammal populations in southeastern Australia, Proceedings of the MEDECOS X1, The International Mediterranean ecosystems conference, eds G. Moss, R.McLellan, G. Wardell - Johnson, Perth, Australia.
Wilson, B.A., Robertson, D., Moloney, D.J., Newell, G.R., Laidlaw, S., 1990. Factors affecting small mammal distribution and abundance in the eastern Otway Ranges, Victoria. *Proceedings of Ecological Society of Australia* 16, 379-394.
Woinarski, J.C.Z., Armstrong, M., Brennan, K., Fisher, A., Griffiths, A.D., Hill, B., Milne, D.J., Palmer, C., Ward, S., Watson, M., Winderlich, S., Young, S., 2010. Monitoring indicates rapid and severe decline of native small mammals in Kakadu National Park, northern Australia. *Wildlife Research* 37, 116-126.
Woinarski, J.C.Z., Armstrong, M., Price, O., McCartney, J., Griffiths, A.D., Fisher, A., 2004. The terrestrial vertebrate fauna of Litchfield National Park, Northern Territory: monitoring over a 6-year period and response to fire history. *Wildlife Research* 31, 587-596.
Woinarski, J.C.Z., Fisher, A., Armstrong, M., Brennan, K., Griffiths, A.D., Hill, B., Low Choy, J., Milne, D., Stewart, A., Young, S., Ward, S., Winderlich, S., Ziembicki, M., 2012. Monitoring indicates greater resilience for birds than for mammals in Kakadu National Park, northern Australia. *Wildlife Research* 39, 397-407.
Woinarski, J.C.Z., Milne, D.J., Wanganeen, G., 2001. Changes in mammal populations in relatively intact landscapes of Kakadu National Park, Northern Territory, Australia. *Austral Ecology* 26, 360-370.
Woinarski, J.C.Z., Winderlich, S., 2014. A strategy for the conservation of threatened species and threatened ecological communities in Kakadu National Park, 2014-2024. North Australian Hub of the National Environmental Research Program, Darwin.

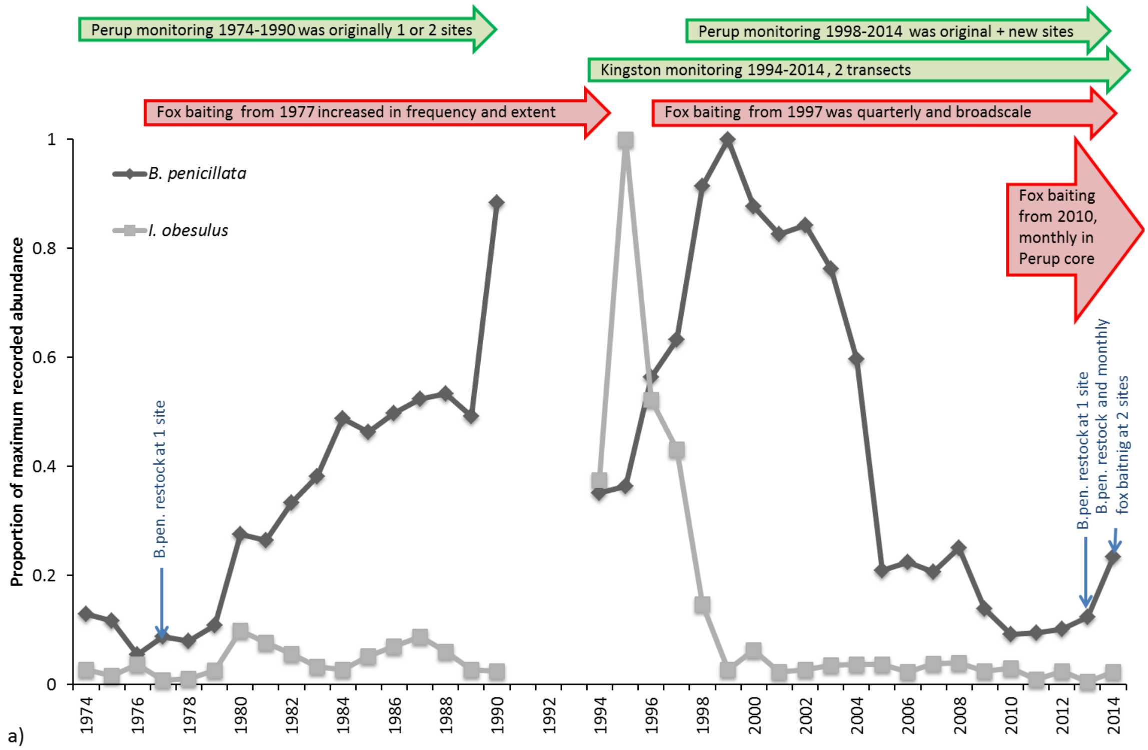
Yeatman, G., 2015. The distribution and abundance of terrestrial vertebrates in the jarrah (*Eucalyptus marginata*) forest, south-western Australia, in relation to habitat at multiple temporal and spatial scales. Ph.D. thesis, University of Western Australia, Perth.

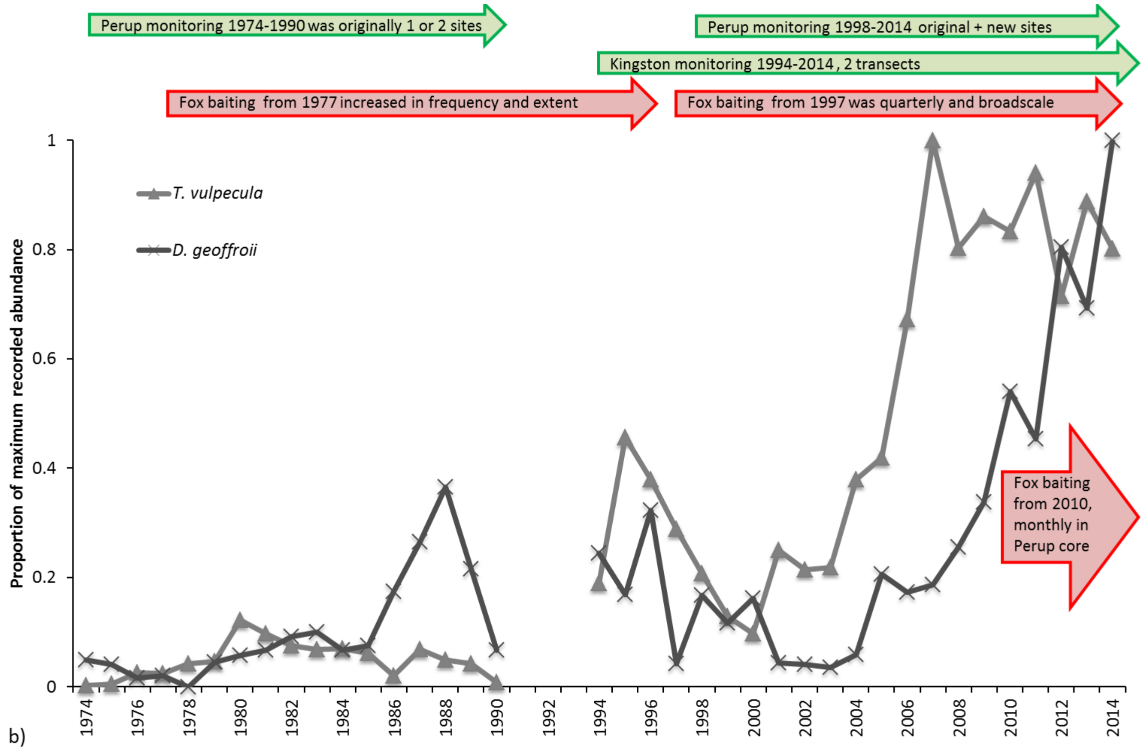
Zosky, K., 2011. Food resources and the decline of woylies *Bettongia penicillata ogilbyi* in southwestern Australia. Ph.D. thesis, Murdoch University, Perth.

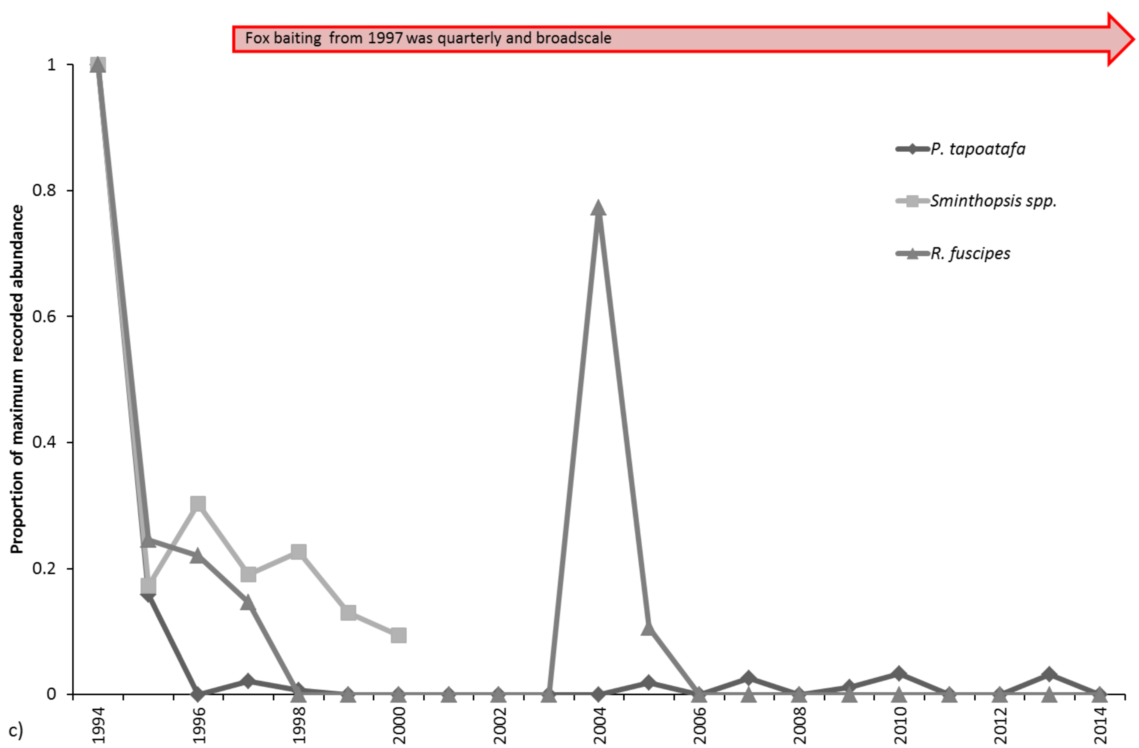
Supplement 2: Longitudinal trends in mammal abundances at the (1) south-western and (2) south-eastern Australian study areas.

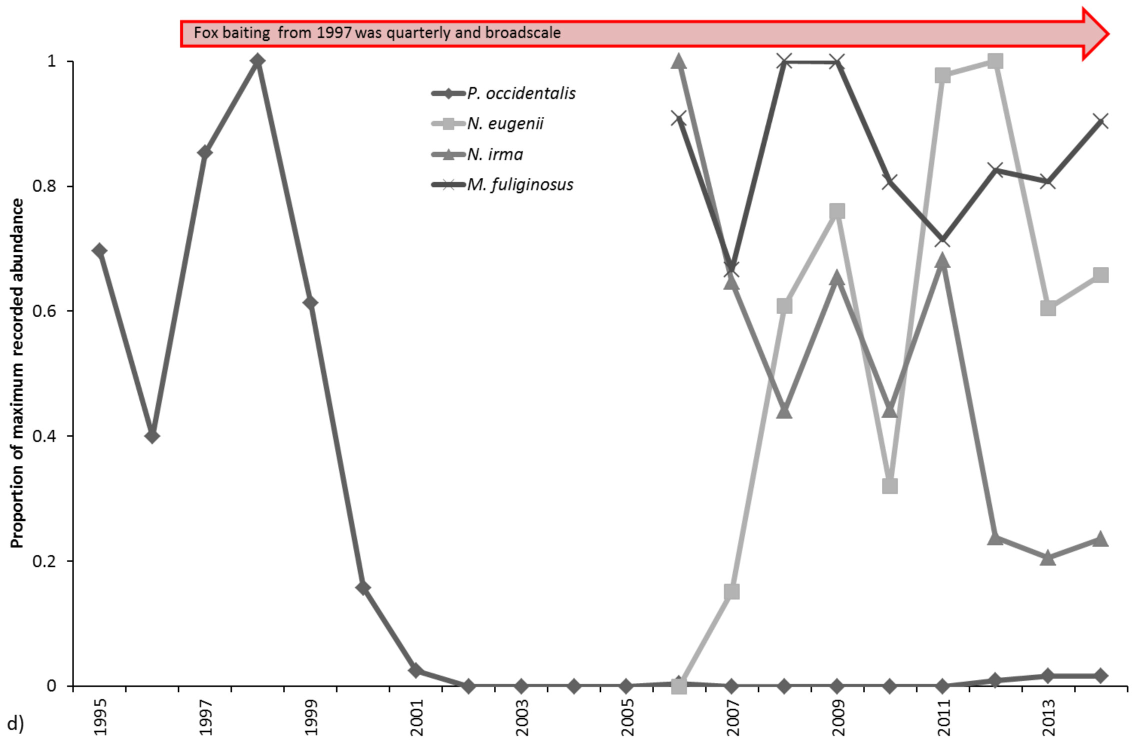
Note that the relatively more straightforward (because they relate mostly to changes simply from a baseline sampling to a single subsequent sampling events) changes observed in the northern study area are not detailed here.

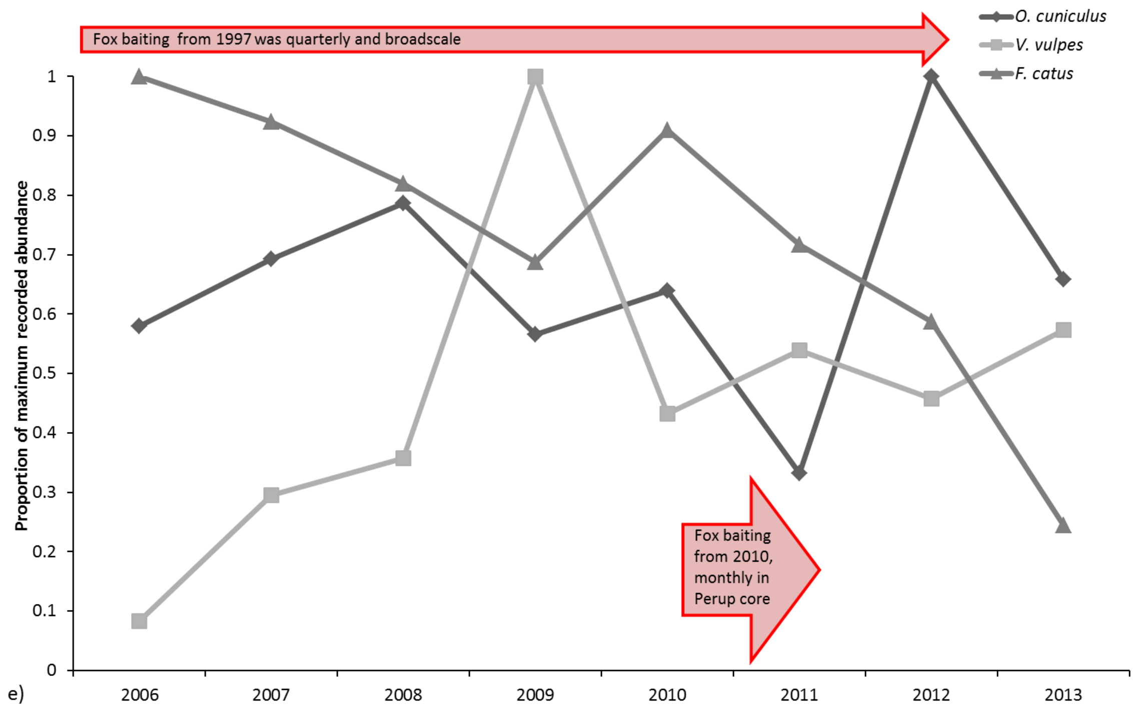
Supplement Figure 2.1. Summary of changing abundance (expressed as the proportion of peak abundance) over the entire monitoring program for all species in all components of the south-western study area. (a) cage-trap transects (n=1-11 per year) – unsustained recovery; (b) cage-trap transects (n=1-11 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).




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
b)


Fox baiting from 1997 was quarterly and broadscale
P. tapoatafa
Sminthopsis spp.
R. fuscipes
Proportion of maximum recorded abundance
c)

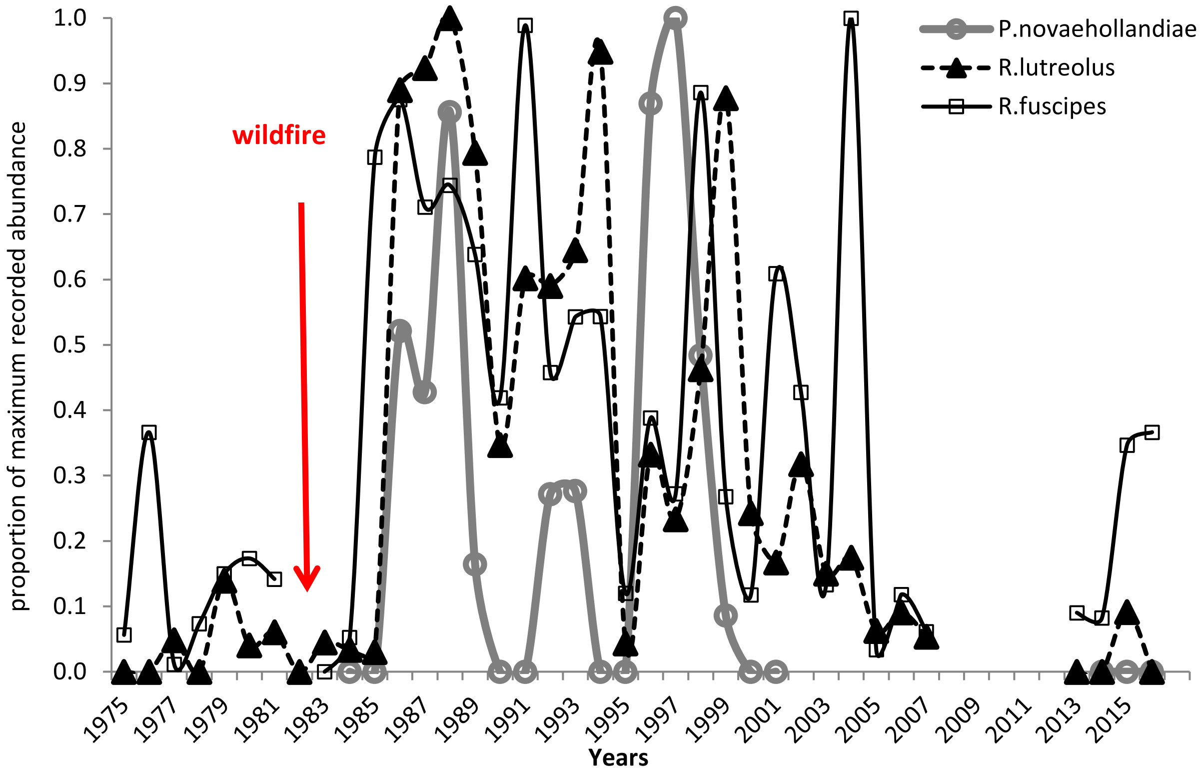

Fox baiting from 1997 was quarterly and broadscale
P. occidentalis
N. eugenii
N. irma
M. fuliginosus
Proportion of maximum recorded abundance
0
0.2
0.4
0.6
0.8
1
1995
1997
1999
2001
2003
2005
2007
2009
2011
2013
d)


O. cuniculus
V. vulpes
F. catus
Fox baiting from 1997 was quarterly and broadscale
Fox baiting from 2010, monthly in Perup core
Proportion of maximum recorded abundance
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2006
2007
2008
2009
2010
2011
2012
2013
e)

Publisher: CSIRO; Journal: Wildlife Research; Article ID: WR16178; DOI: 10.1071/WR16178

Supplementary Figure 2.2. 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.

a)



b)

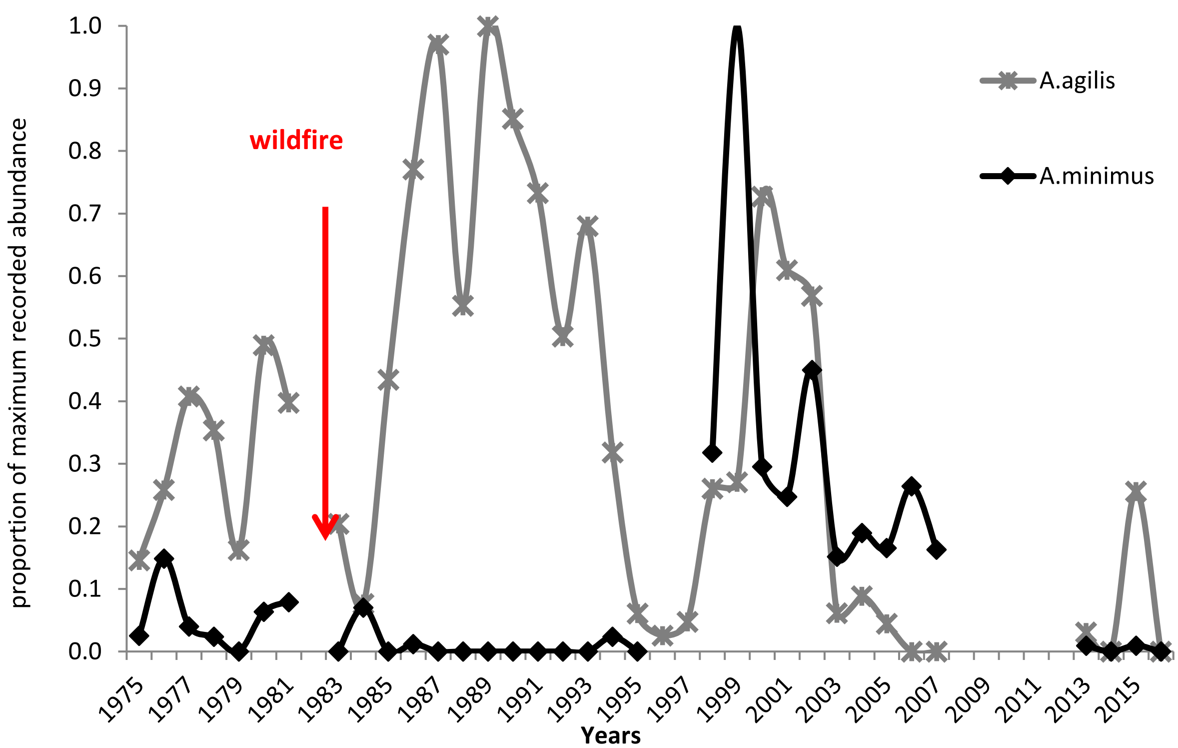


Table 1. Changes in abundance of mammal species for the south-eastern study. Values are the change in abundance (trap success rate) from baseline (first two years) to final two years.
n= number of sites, PF = Post Fire (monitored prior to and after 1983 Ash Wednesday Wildfire), with sites H=Harvey; R=Reserve; 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