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Prioritisation of conservation research and monitoring for Western Australian protected areas and threatened species

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ABSTRACT

Prioritisation of natural assets for monitoring and research activities facilitates equitable allocation of finite conservation resources. We present a framework that identifies broad monitoring and research priorities for conservation areas, such as marine parks, and threatened species. Criteria within the framework are used to assess: the value (V) of assets; anthropogenic pressures (P) that affect assets; and the current state of asset knowledge (K). A panel of experts score criteria and the relative importance of each asset is calculated for monitoring (V * P), fundamental research (V * K) and applied research (V * P * K). The framework allows prioritisation of assets in an initial evaluation that agrees with institutional mandates, and facilitates future assessment of the feasibility and cost of monitoring or research in the implementation phase. The utility of the framework is that it can be easily applied by conservation practitioners and can concurrently prioritise monitoring and research of species, habitats and communities in marine and terrestrial environments.

Keywords: prioritisation framework, condition–pressure–response monitoring, marine protected area, Ningaloo

INTRODUCTION

Robust conservation and natural resource management decisions must be founded on sound scientific knowledge (Roux et al. 2006). However, there is often a mismatch between research effort and conservation needs (Fisher et al. 2010). For this reason, it is imperative that management for protected areas and threatened species identify and prioritise knowledge gaps that constrain effective management, and that these gaps be addressed by targeted research and monitoring activities (Field et al. 2005; Fancy et al. 2009). Given the number and diversity of possible research and monitoring actions, managers must also prioritise activities to ensure the effective use of limited resources (Wilson et al. 2006). Employing a structured and consistent quantitative approach to prioritising research and monitoring activities enables managers to make decisions that are transparent, reviewable and adaptive (Day 2008). This provides a structured and informed decision-making process that avoids personal bias and is scientifically defendable.

A structured and consistent framework to prioritise research and monitoring for biodiversity conservation and natural resource management should incorporate a broad range of environmental, social, cultural and economic parameters (Given & Norton 1993; Suter 2006; Bryan et al. 2010a). Such a framework should be founded on robust conceptual models and where possible, be supported by quantitative information (Possingham et al. 2001; Lindenmayer & Likens 2009). The process should, however, be flexible enough to use the informed consensus of experts in the absence of quantitative data to provide robust outcomes (Feary et al. 2014; Ward 2014a). The broad utility of such a framework is enhanced through the use of simple assessment metrics and computations that avoid the need for complex computer software or particular staff expertise (Cullen et al. 2013; Pannell et al. 2013). This increases the potential for engagement and participation in the process whilst maximising transparency of the prioritisation decisions and avoiding delays in progressing research and monitoring activities.

Prioritisation frameworks have previously been developed to assess conservation priorities spatially (Groves et al. 2002; Margules & Pressey 2000; Margules et al. 2002), by species (Coates & Atkins 2001; Arponen 2012; Hiscock et al. 2013) and using simplified links to pressures (Moorcroft et al. 2012). There has, however, been less emphasis on prioritizing research and monitoring activities for the suite of biophysical assets within established protected areas or for species already under conservation management (but see Grech & Marsh 2008; Ward 2014a). Management plans for protected areas or species typically identify important assets and the human pressures that influence asset condition (e.g. CALM 2005). Assets are identified on the basis that they have special conservation value, are unique to the area, are key structural components of the system, or have commercial and/or other social value (Groves et al. 2000; Wilson et al. 2005; Natural Resource Management Ministerial Council 2010). Management plans, however, contain multiple assets and associated pressures, generally with no indication of their relative importance, making it difficult to assess where research and monitoring is most warranted (Knight et al. 2009). Identifying research and monitoring priorities may be further hindered by limited information on assets or the probability and consequences of threatening processes, making it difficult to determine their relative impact upon the suite of biophysical assets within the protected area or threatened species (Brooks et al. 2006; Arponen 2012). For this reason, any framework should consider the current state of knowledge, both of assets and threatening processes, as a mechanism to highlight information gaps and direct research and monitoring towards clear areas of need.

Previous research has also emphasised the importance of project costs (Possingham & Wilson 2005; Wilson et al. 2006) and effectiveness (Cullen 2013), which may be used to undertake cost benefit analyses when prioritising actions (Joseph et al. 2009). However, our objective is not to evaluate and compare specific projects or actions, but to identify assets or species that warrant research and monitoring attention. This is akin to a filtering stage that is undertaken before comprehensive cost–benefit analysis (Pannell et al. 2013) and allows a broad prioritisation prior to the development of specific projects. Moreover, calculating the economic benefit of environmental research and monitoring is often difficult and time consuming, particularly when these values are not easily quantified or tangible. It is therefore prudent to only undertake cost–benefit analyses on projects that address topics of most concern.

Accordingly, we present a semi-quantitative assessment framework to prioritise research and monitoring for the conservation of protected areas and threatened species. The framework considers the relative conservation 'value' (based on ecological and social criteria) of each asset and links this with measures of current management-related knowledge and the relative significance of relevant threatening processes (i.e. pressures). Based on this premise, we describe the framework and the associated equations and then apply these to the assets of Ningaloo Marine Park (NMP) in Western Australia to demonstrate how the framework could be used to identify research and monitoring topics of high priority.

THE PRIORITISATION FRAMEWORK

The prioritisation framework is based on the construction of a matrix of the assets of interest (e.g. assets identified within a marine protected area, or suite of threatened species), and a series of criteria used to assess the relative value of assets (V), the pressures (P) acting on the assets and the adequacy of management-related knowledge (K) relating to each asset. Research and monitoring priorities are determined based on rankings of these criteria (e.g. using scores from 1 = low to 3 = high). When criteria listed are independent of each other, the scores are added but when criteria are clearly related, a geometric mean is calculated. Combined this provides a systematic attempt to set research and monitoring priorities.

Ranking the relative significance of asset value (V)

Ecological and social values of an environmental asset are often disparate and it is important to consider criteria that relate to both these aspects when assessing asset value (Marsh et al. 2007; Bryan et al. 2010a). Moreover, assets within marine parks may be of a physical nature (e.g. geomorphology), and biological characteristics of species are often important when prioritising threatened species (Williams et al. 2008). Consequently, the relative value of assets is determined from ten criteria (Table 1) that relate to ecological role (V_{1-3}) social importance (V_{4-7}) and ecological robustness (V_{8-10}). The relative value of each asset can then be determined by summing the geometric means (Π) of similar criteria:

$$V = ((\Pi\ V_{1-3})^{1/3} + (\Pi\ V_{4-7})^{1/4} + (\Pi\ V_{8-10})^{1/3}).$$

Ranking the relative significance of pressures (P)

For conservation purposes, pressures can be defined as human activities that potentially or actually impact on assets at a scale that is receptive to the influence of management. It is therefore imperative that prioritisation frameworks consider the relative importance of different pressures (Evans et al. 2011; Murray et al. 2011). Here, the consequences of a pressure are assessed as the geometric mean of four criteria (P_{1-4}), whilst the likelihood of that pressure occurring is measured by P_5 (Table 2). Consistent with the concept of risk-ranking assessment (AS/NZS 2009; Burgman 2005), the overall significance of a pressure is then expressed as a function of consequences and likelihood of occurring:

$$P = ((\Pi\ P_{1-4})^{1/4})^{*}P_5.$$

Table 1

Criteria used to assess the ecological, biological, physical and social value of assets. Numerical values in parentheses are indicative of appropriate scores for each criterion.

Criteria	Intent of the criteria
Foundation habitat or habitat forming biota (V1)	To identify physical characteristics, communities or species that create key habitats (Dayton 1972). Those assets that form the basis of the habitat (e.g. corals and sediment) score high (3) against this criterion, whilst assets that modify the habitat (e.g. herbivores) will score moderately (2) and those that only use the habitat for food or shelter will score lower (1).
Ecosystem processes (V2)	To recognise that some assets support a broader array of key ecosystem processes than others (Daily 1997, 2000). Seagrass, for example, is a primary producer, provides refugia, stabilises sediments (Orth et al. 2006) and would score high for this criterion (3), as would keystone species (2), which exert a disproportionally high influence on their surrounding environment relative to their abundance (Marsh et al. 2007).
Uniqueness (V3)	To recognise local physical assets or species that are exceptional relative to other areas. Assets with a relatively limited distribution (e.g. endemic species or distinctive geological formations) or assets with exceptional quality, abundance or composition in relation to other areas will score higher (3) than those assets that are relatively well represented elsewhere (2), or those that have no outstanding local characteristics (1).
Cultural (V4)	To take account of the cultural significance of an asset in relation to its physical or spiritual heritage and iconic status (Navrud & Ready 2002; Speed et al. 2012). Some assets have significance because they are an integral component of one culture or they are valued by several cultures for multiple reasons and will score high (3) against this criterion (e.g. whales). Other assets have limited (2) or no apparent cultural value (1).
Recreational (V5)	To recognise that some assets are valued as they support recreational activities which have an inherent value or worth for the community (Brander et al. 2007). Assets that have extensive existing (3) or potential (2) importance for recreational activity (e.g. diving locations, wildlife watching or recreational fishing) will score high against this criterion.
Economic (V6)	To recognise the economic value associated with an asset (Daily 1997). Assets that directly contribute to an economic activity (e.g. fish for artisanal or commercial fisheries, aquaculture or nature-based tourism) will score high (3) against this criterion. Assets that support economically important species or services (e.g. seagrass for prawn fisheries) or have potential economic importance (e.g. seaweed as biofuels) would rate moderately (2) and assets with no apparent economic value will score low (1).
Scientific (V7)	To recognise that some assets attract high levels of scientific interest because of their intrinsic value (e.g. rare marine stromatolites) and/or because the scientific community values a unique or extensive data resource relating to the asset (Reynard et al. 2007). Assets that are recognised for their broad scientific significance and attract interest from multiple, independent research groups will score high (3) against this criterion. Assets that have some interest from at least one research group will score moderately (2) and assets with no ongoing research interest will score low (1).
Historical perspective (V8)	To recognise that some assets may have had a higher value in the past but have been subjected to significant pressures resulting in a current condition that is highly modified. For example, although cetaceans are no longer hunted in Australia, their populations remain depleted and are still recovering (Alter et al. 2012). Assets that are in a degraded or depleted condition irrespective of current pressures will score highly (3) under this criterion, while those that are recovering will score moderately (2) and those with no evidence of historic degradation will score low (1).
Vulnerability (V9)	To recognise that some assets are highly susceptible to degradation by natural and/or anthropogenic pressures, whilst others are resistant (Burgman 2005). Assets susceptible to a variety of common pressures will score higher (3) against this criterion compared to those that are susceptible to few pressures (2) or those with a higher resistance to disturbance that are rarely affected (1).
Recovery potential (V10)	To place greater emphasis on assets that have a limited capacity to respond to disturbance and recover to their prior state (Pimm 1984; Brand & Jax 2007) Thus, those assets with traits that confer low rates of recovery (e.g. coastal geomorphology following development) will score higher (3) against this criterion than assets with moderate (2) or rapid (1) recovery trajectories.

Ranking the adequacy of existing knowledge (K)

Research priorities for conservation should be guided by gaps in the current state of fundamental knowledge and the information requirements of conservation practitioners (Jennings 2000). The adequacy of knowledge relating to assets, and the pressures acting on them, is determined from four criteria (Table 3). Two of these criteria, inventory (K_1) and baseline (K_2), are spatially explicit and require knowledge that is relevant to the area of interest. However, knowledge of ecological and physical processes (K_3) and modelling to identify management targets (K_4) may be relevant even when it is not drawn directly from the area or species of interest. The lack of knowledge can be assessed by:

$K = (4 - (\Pi\ K_{1\text{–}4})^{1/4}) * 3.$

The lack of knowledge value is multiplied by 3 so the potential range of 1–9 is the same as V and P values, ensuring V, P and K have equal weighting when calculating research and monitoring scores.

Fundamental Research

Fundamental (or strategic) research provides knowledge of natural systems that is required for effective ecosystem-based management without directly addressing the management of pressures. As such, fundamental research may characterise the ecological and cultural values of an area, investigate key ecological and social processes or determine natural patterns of spatial and temporal variability, thus providing information on the background patterns of natural dynamics for estimating the scale and significance of human-induced change. The importance of undertaking fundamental research (FR) on a particular asset will therefore be a function of its relative ecological value (V) and the extent of existing knowledge (K):

$FR = V * K.$

Applied Research

Applied research seeks to understand how natural systems respond to anthropogenic pressures and the mitigation strategies that might be used to ameliorate them. Studies that investigate human usage patterns and attitudes, and interactions between human pressures and values are examples of applied research that aim to address foreseeable or immediate management issues. The relative importance of undertaking applied research (AR) on a particular asset is a function of its value (V), the pressures acting on it (P) and the current knowledge of the interaction between the asset and that specific pressure (Kp). The criteria and scoring scale used to calculate Kp are the same as those used when calculating K, although Kp explicitly assesses knowledge on how a particular pressure influences an asset's condition:

$AR = V * P * Kp.$

Monitoring

Monitoring provides time-series data to help understand inherent variability and manage human activities that place pressure on the environment. Importantly, monitoring programs should reconcile the spatial and temporal scales of assets under threat relative to identified pressures (Chapman 2012). This approach applies to both short-term compliance-type monitoring programs with very specific management targets, and longer-term surveillance-type monitoring programs that assess the nature, extent and frequency of natural and human pressures. Moreover, condition–pressure–response monitoring requires periodic measurements of asset condition, the significance of pressures acting on the asset and the resources invested in management, with the overall aim of assessing the effectiveness of management (Ward 2000; Burgman 2005; Thomas 2005). Should, for example, asset condition deteriorate with a linked increase in a particular pressure, management settings or resourcing can be altered to counter such a trend (Lindenmayer et al. 2013). The priorities for monitoring relate to the value (V) of the asset and the significance of the pressures (P) acting on it. As such, monitoring (M) should be a clearly linked function of a specific pressure–asset interaction:

$M = V * P.$

Project development

This framework identifies assets that warrant research and monitoring attention, but does not identify or prioritise specific projects. Nonetheless, the development of research projects can be guided by the criteria that promoted high research scores. For fundamental research, this will reflect the extent and type of knowledge currently available, whilst applied research projects should relate to knowledge relevant to the pressure–asset/species interaction. The spatial and temporal extent of high priority monitoring projects will be informed by the distribution of key pressures in space and time. Detailed assessment of the costs, benefits, feasibility and uptake of projects can then be used to identify those of highest priority (Pannell et al. 2013).

NINGALOO MARINE PARK: AN EXAMPLE OF HOW THE FRAMEWORK COULD BE USED

To demonstrate how the framework could be applied, monitoring and research priorities were identified for the NMP. Assets were restricted to ecological key performance indicators of management effectiveness in the 2005–2015 NMP Management Plan (CALM 2005). These assets were scored using criteria in Tables 1 and 3 to assess their relative values and current extent of knowledge. The main pressures acting on each asset were also drawn from the management plan and were scored for the ensuing 10-year period using criteria in Table 2. Climate change was also recognised as an important driver of prioritising conservation activities (Hodgson et al. 2009; Natural Resource Management Ministerial Council 2010; Iwamura et al. 2013); and although this is not listed in the management plan, it is included as a pressure that

Table 2

Criteria used to assess pressures. Values in parentheses are indicative of appropriate scores for each criterion.

Criteria	Intent of the criteria
Spatial scale (P1)	This criterion assumes that the greater the spatial extent of a pressure in relation to the spatial distribution of the asset, the greater the management concern (Thrush et al. 1998; Clavero et al. 2010). Pressures resulting in widespread impacts across an entire region would be given a higher score (3) than those that cause multiple (2) or isolated (1) localised impacts.
Temporal scale (P2)	This criterion acknowledges that sustained pressures are generally of greater management concern than short-lived pressures (Hughes et al. 2003). Sustained pressures will score higher (3) than occasional but short-lived (2) or rare (1) pressures.
Biological severity (P3)	The ramifications of some perturbations can have greater biological consequences than others for an asset. For example, fishing is expected to have a greater effect on the abundance and long-term survival of targeted fish species than climate change (Graham et al. 2011). Pressures that have a severe impact on an asset and have consequences over ensuing years to decades will score highly against this criteria (3) relative to pressures that have consequences that last months to years (2) or are negligible (1) (Fletcher 2005).
Socio-political implication (P4)	This criterion acknowledges that pressures have different social, economic, cultural and political consequences (Suter 2006). A pressure that creates a high social/political consequence, inducing immediate management or stakeholder response, will score highly (3) for this criterion whilst pressures that attract social attention but no response will score moderately (2) and those that attract no attention will score low (1).
Likelihood (P5)	This criterion addresses the probability of a pressure occurring within a specified timeframe (Burgman 2005). Pressures that exist or are expected to occur within the timeframe established for the prioritisation matrix will score higher (3) than those with possible (2) or a remote (1) probability of occurring (adapted from Fletcher 2005).

Table 3

Criteria used to assess scientific knowledge related to an asset. Values in parentheses are indicative of appropriate scores for each criterion.

Criteria	Intent of criteria
Inventory (K1)	This criterion assesses the existing level of descriptive, qualitative or quantitative information on the asset (e.g. initial surveys of seagrass biomass and distribution, or species lists). Scores are high (3) if a comprehensive and verified inventory is available and moderate (2) if only limited data exists and low (1) if no data exists.
Baseline (K2)	This criterion assesses whether there is adequate quantitative spatial and temporal information to express the ‘natural’ state of an asset and distinguish between natural variability and human influences. Adequacy of baseline data is measured in both temporal and spatial terms. The presence of long-term, spatially representative datasets would score high (3) for this criterion whilst spatially extensive short-term, or long-term localised data sets would score moderately (2) and data with no temporal or spatial replication would score low (1).
Processes (K3)	This criterion assesses whether adequate information exists to identify and quantitatively assess processes that influence the condition of the asset (e.g. growth and reproduction). Regional-scale knowledge of relevant processes may be applicable even when knowledge was not collected locally. If current knowledge allows multiple key process parameters to be readily identified and quantified a high score (3) would be recorded. When key processes are identified but not quantified a moderate (2) score will be recorded and no reliable process information warrants low score (1).
Management targets (K4)	This criterion assesses whether the level of knowledge is adequate to be used to model the consequences of changing pressures and set ecologically sustainable management targets (Ferrier 2012). Regional scale knowledge of relevant modelling parameters may be applicable even when knowledge was not collected locally. The score increases as the level of understanding of the cause-effect pathways becomes clearer. When knowledge is sufficient to set robust management targets for asset condition, associated pressures and management actions, the score against this criterion will be higher (3), than when uncertainty around these targets is unacceptable (2) or there is insufficient data to calculate targets (1).

impinges upon all the considered assets. The final scores for each value, knowledge and pressure criteria were based on average values from independent assessments by four of the co-authors, all of whom possess significant (5+ years) research and/or management knowledge of NMP. Average scores, with 95% confidence intervals, were then used to assess variance among participants and identify research and monitoring activities of similar priority. A more comprehensive assessment of assets should incorporate independent scores from a broader array of scientists, managers and stakeholders to capture all levels of relevant expertise and experience.

Coral reefs, finfish and turtles had the highest relative value among the assets; however, knowledge relating to management of these NMP assets is extensive, and they were not considered a high priority for fundamental research. Conversely, knowledge on water quality is low for NMP, especially baseline information. Therefore, fundamental research is required on this topic (Table 4).

The most significant pressure acting across all key performance assets for NMP was climate change, whilst fishing was also a major pressure on finfish (Table 5). Accordingly, applied research projects should focus on the effects of climate change on corals, finfish, mangroves and turtles, with emphasis on developing predictive models. In addition, high scores were achieved by the effects of fishing and habitat loss on finfish, as well as the effects of groundwater removal on mangroves. Applied research projects on finfish might focus on better understanding key processes and modelling impacts of fishing and habitat loss, whilst inventory and baseline information is required to better understand interactions between groundwater levels and mangrove persistence. Monitoring priorities should focus on assets and associated pressures with high scores. At Ningaloo, this includes projects that monitor the effects of climate change on coral, finfish and turtles, as well the impacts of fishing on finfish.

DISCUSSION

The framework presented here provides a clear process for identifying research and monitoring priorities for protected areas and threatened species by concurrently assessing asset values, pressures and the current extent of knowledge. The utility of this framework enables the criteria to be easily evaluated in a manner that provides a consistent, transparent and defensible set of research and monitoring priorities for managers. Such outcomes are important because conservation resources are often inadequate and managers must be able to demonstrate that their limited research and monitoring capacity is directed to areas of greatest strategic need (Hughey et al. 2003; Marsh et al. 2007). Conservation science competes for funding with other societal priorities, severely constraining the availability of resources for research and monitoring (Wilson et al. 2009). Despite limited resources, we contend that monitoring, fundamental and applied research are complementary and equally important aspects of building knowledge to ensure that management decisions are based on sound science.

By using this framework to prioritise research and monitoring activities in NMP, we have shown that fundamental research on water quality is a high priority, whilst applied research and monitoring should focus on the effects of climate change on corals and turtles and the influence of fishing on finfish. The emphasis on climate change and fishing acknowledges the direct impact that these pressures can have on assets of high ecological and social value (Jennings & Kaiser 1998; Hughes et al. 2003), and the importance of research and monitoring to understand the impacts of these pressures (Fisher et al. 2011). Findings are also consistent with a recent assessment of the Great Barrier Reef that found climate change, water quality and extractive activities pose the greatest threat to ecosystem health (Ward 2014b). The primary objective here was, however, to demonstrate how

Table 4

Fundamental research (FR) priorities for key performance assets at NMP. Criterion scores, mean and 95% confidence intervals (CI) for FR calculated from four independent scores. Based on 95% CI, the values in red are the highest.

	Value											Knowledge							
Asset	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9	V_{10}	V	K_1	K_2	K_3	K_4	K	FR mean	FR lower 95% CI	FR upper 97% CI
Coral reefs	3.0	2.0	1.8	2.0	3.0	2.0	2.0	2.3	3.0	2.0	6.7	3.0	3.0	3.0	2.0	3.9	26.0	24.7	27.3
Finfish	1.8	2.0	1.0	3.0	3.0	3.0	2.0	3.0	2.0	1.0	6.0	3.0	3.0	2.0	2.0	4.7	28.1	27.3	28.8
Mangroves	3.0	1.8	1.0	1.0	2.0	2.0	1.0	1.0	2.0	2.0	4.7	3.0	2.0	2.0	2.0	5.4	25.3	24.3	26.3
Turtles	1.3	1.3	1.3	3.0	2.0	2.0	3.0	3.0	3.0	2.0	6.3	3.0	3.0	2.0	2.0	4.7	29.2	28.0	30.5
Water quality	2.5	3.0	2.0	2.0	2.0	2.0	1.0	1.0	2.0	1.0	5.4	2.0	1.0	2.0	2.0	7.0	37.3	34.5	40.0

V1 Foundation habitat; V2 Ecosystem processes; V3 Distribtion; V4 Cultural; V5 Recreational; V6 Economic; V7 Scientific; V8 Historical perspective; V9 Vulnerability; V10 Resilience; K1 Inventory; K2 Baseline; K3 Model parameters; K4 Predictive models

Table 5

Applied research (AR) and monitoring (M) priorities for key performance assets at NMP. Criterion scores, mean and 95% confidence intervals (CI) for AR and M calculated from four independent scores. Based on 95% CI, the values in red are the highest.

		Pressure						Knowledge										
	V	P_1	P_2	P_3	P_4	P_5	P	K_1	K_2	K_3	K_4	Kp	AR mean	AR lower 95% CI	AR upper 95% CI	M mean	M lower 95% CI	M upper 95% CI
Coral reefs–																		
Visitor	6.7	1.0	1.8	2.8	1.0	3.0	4.4	3.0	2.3	2.8	2.0	4.6	137.5	124.2	150.7	29.6	26.7	32.4
Oil spill	6.7	2.8	1.0	1.8	3.0	1.0	1.9	3.0	1.8	2.0	1.0	6.6	86.3	73.9	98.7	13.0	11.7	14.2
Climate change	6.7	2.8	2.8	3.0	3.0	2.8	7.9	2.8	2.0	2.8	1.8	5.2	267.5	249.4	285.7	53.2	41.1	65.3
Finfish–																		
Fishing	6.0	2.3	2.8	2.8	2.0	2.8	6.6	3.0	2.3	2.0	2.0	5.2	210.4	150.8	270.1	40.1	30.6	49.6
Fish feeding	6.0	1.0	2.0	1.3	1.8	2.3	3.3	2.8	1.8	1.8	1.3	6.6	126.9	100.9	152.9	19.4	14.4	24.3
Loss of habitat	6.0	2.0	2.3	2.3	1.5	2.3	4.4	2.8	2.5	1.8	1.5	5.8	164.4	75.4	253.3	26.6	18.6	34.5
Climate change	6.0	2.5	2.0	2.3	1.8	2.5	5.3	2.3	2.0	1.8	1.0	7.0	220.7	159.6	281.8	32.0	21.1	42.9
Mangroves–																		
Trampling	4.7	1.0	1.8	1.3	1.0	3.0	3.6	2.8	1.8	1.8	1.0	6.9	116.8	98.0	135.6	16.9	16.2	17.5
Oil spill	4.7	2.5	1.3	2.5	2.5	1.0	2.1	1.8	1.3	1.3	1.3	7.9	78.4	70.1	86.7	9.7	8.9	10.4
Water extraction	4.7	2.5	2.8	1.5	1.8	2.0	4.1	1.3	1.3	1.3	1.0	8.5	161.1	131.3	191.0	18.9	16.9	20.9
Climate change	4.7	2.3	2.5	1.8	1.5	2.3	4.4	2.3	1.8	1.8	1.8	6.4	138.5	65.1	211.8	21.3	10.9	31.7
Turtles–																		
Invasive predators	6.3	2.8	2.8	1.0	1.3	2.3	3.9	3.0	3.0	3.0	2.0	3.9	93.4	76.8	110.1	24.2	19.9	28.5
Visitor	6.3	1.0	2.0	2.8	1.3	3.0	4.9	2.0	2.0	2.8	2.8	5.0	150.0	127.3	172.6	30.0	28.9	31.2
Climate change	6.3	3.0	2.8	2.3	2.3	2.5	6.4	2.3	1.8	2.3	1.0	6.8	274.9	188.7	361.2	40.1	28.1	52.0
Water quality–																		
Sewage input	5.4	1.0	1.8	3.0	1.3	1.0	1.6	2.3	2.0	2.5	1.8	5.7	47.9	45.4	50.5	8.4	7.8	9.0
Oil spill	5.4	2.3	1.5	3.0	3.0	1.0	2.3	2.3	1.3	1.5	1.3	7.5	93.9	73.6	114.2	12.4	11.4	13.3
Litter	5.4	1.3	1.8	1.3	1.8	2.3	3.3	2.5	2.3	1.8	1.8	5.9	102.5	65.4	139.7	18.4	8.5	28.3
Climate change	5.4	3.0	2.3	1.5	2.3	1.5	3.3	2.3	1.5	1.8	1.5	6.8	120.7	67.8	173.6	17.8	9.3	26.3

P1 Spatial scale
P2 Temporal scale
P3 Biological severity
P4 Social/political implications
P5 Likelihood
K1 Inventory
K2 Baseline
K3 Model parameters
K4 Predictive models

the framework could be applied. An assessment of all assets in the NMP Management Plan by a broader suite of participants is warranted.

The framework has potentially broader application in both marine and terrestrial systems, and may be used to prioritise research and monitoring for a range of conservation management scenarios where one or more assets are subject to different pressures, and the state of knowledge of each asset varies. When using the framework for alternative scenarios it may be necessary to modify criteria to ensure they are appropriate for the range of assets in question. If, for example, the framework were used to prioritise research and monitoring for marine mammals, the criteria could be customised to ensure that variation among species is recognised. In particular, marine mammals are typically long-lived, slow breeders, and have inherently similar levels of vulnerability when this criterion is based solely on life history traits (Marsh et al. 2003). Consequently, variation in the vulnerability criterion (V_9) could be driven by availability of suitable habitat and current population size (Simmonds & Isaac 2007). Such flexibility enables management agencies to use a consistent and defendable method of determining research and monitoring priorities across what are commonly broad-ranging conservation responsibilities.

The framework is also flexible in relation to the relative importance of the criteria, and can be modified by removing, adding or weighting criteria. Weighting of criteria can be undertaken using an Analytical Hierarchy Process, AHP (Saaty 1980), which is based on pairwise comparisons of criteria importance by experts, an approach that has been used in other frameworks (e.g. Bryan et al. 2010b; Graham et al. 2011).

A major limitation of many prioritisation processes is that scoring may be biased by the prejudices of the experts involved (Master 1991; Drescher et al. 2013). This subjectivity may be overcome by having a diverse group of people score criteria. For example, Fleishman et al. (2010) used an open participation process that encouraged hundreds of scientists and managers to identify conservation priorities. Incorporating opinions from a large and diverse number of participants should reduce personal bias, although any inherent prejudices of participants may be assessed by asking each about their background and determining if they place higher prioritization on areas that reflect their interests (Wilson et al. 2010). Importantly, the mechanism by which participants are identified and selected must be transparent and repeatable (Burgman et al. 2011; Drescher et al 2013). Magos Brehm et al. (2010) ranked the conservation importance of plant species using four different assessment computations of the same prioritisation criteria. The order in which species were ranked differed among the computations, although some species consistently ranked above others and were appropriately identified as high conservation value. These results indicate that there is considerable variance among prioritisation frameworks, but high priority projects, species or areas may be identified from congruent patterns among a composite of processes.

Determining threshold scores for high, medium or low priority research and monitoring activities is another potentially subjective process associated with the framework. However, treating the prioritisation criteria as a multivariate data set allows research and monitoring activities to be plotted in multidimensional space and clusters of activities of similar priority to be identified (Given & Norton 1993).

Establishing research and monitoring priorities provides a more structured basis for the equitable allocation of conservation resources. The framework presented here identifies biophysical assets and species that warrant the greatest monitoring, fundamental or applied research. The framework incorporates information on asset value, the anthropogenic pressures that impinge upon those assets and the current knowledge relating to the asset or asset–pressure interaction. As priority-informed research and monitoring programs are implemented and completed the accrued information will, however, fill knowledge gaps and as K approaches zero, the emphasis for further research will be reduced. Moreover, evolving knowledge may alter perceptions of pressures and values. To maintain relevant research and monitoring priorities and the efficient use of resources new information should therefore be regularly collated and the prioritisation process repeated.

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The diet of foxes (*Vulpes vulpes*) in fragmented Wheatbelt reserves in Western Australia: implications for woylies (*Bettongia penicillata*) and other native fauna

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ABSTRACT

The diet of foxes in two fragmented Wheatbelt reserves in south-west Western Australia, Dryandra Woodland (DW) and Tutanning Nature Reserve (TNR), was investigated. Fox baiting commenced in these reserves in the early 1980s and the trap success of woylies (*Bettongia penicillata*), a threatened species, increased significantly. Woylie capture rates were sustained in TNR until 1992 and in DW until 2000 but then decreased suddenly despite ongoing fox control. The diet of foxes was investigated as part of a larger study examining the reasons for the woylie decline. The contents of 283 fox scats from DW and TNR, and 167 scats from two unbaited sites, Quinns block (QB) and Highbury block (HB), were analysed volumetrically to determine the relative importance of each dietary item. The actual consumption of each item was calculated using digestibility estimates. In baited sites the foxes' main dietary components were house mice (*Mus domesticus*, 28%), carrion (sheep, *Ovis aries* and western grey kangaroo, *Macropus fuliginosus*; 26%) and rabbits (*Oryctolagus cuniculus*, 17%). In unbaited sites the main components were carrion (predominately sheep, 60%) and some invertebrates (13%). Only one scat (from DW) contained any woylie remains. Approximately 10% of the foxes' diet in all sites consisted of brush-tail possums (*Trichosurus vulpecula*). No remains from numbats (*Myrmecobius fasciatus*), bilbies (*Macrotis lagotis*), red-tailed phascogales (*Phascogale calura*), *Antechinus* sp., *Sminthopsis* sp. or echidnas (*Tachyglossus aculeatus*) were detected. Birds (<5%) and reptiles (<2%) were of little dietary importance at all sites. There was no significant seasonal variation in the foxes' diet. The role of rabbits in the diet of foxes and the potential for the presence of this species to drive increases in fox abundance, and by deduction to increase predation on woylies and other similar prey species, is considered in relation to theoretical predator prey models and management options.

Keywords: *Bettongia*, diet, fox, predation, threatened species, woylie

INTRODUCTION

Australia has the highest rate of mammalian decline and extinction in the world (Short & Smith 1994). Many of these declines coincided with the introduction of the European fox (*Vulpes vulpes*) and its spread across most of southern Australia (Abbott 2011). Due to this, and other evidence, fox predation is now listed nationally as a Key Threatening Process in the decline of vulnerable Australian fauna (Department of Environment, Water, Heritage and the Arts 2008).

The impact of foxes on native Australian mammals is exemplified by the changing status of the woylie (*Bettongia penicillata*: Potoroidae). Woylies occupied large expanses of arid and semi-arid Australia before European settlement but their populations have declined by >99% Australia-wide. In Western Australia the decline coincided with the arrival of the fox between 1910–1930 (Abbott 2002, 2008; Short et al. 2005), and only three populations remained (de Tores & Start 2008). Fox predation on woylies in two of these populations, Dryandra Woodland (DW) and Tutanning Nature Reserve (TNR), may have been mitigated by the presence of a dense understorey of *Gastrolobium* spp. (poison peas) that provided a predation refuge (Christensen 1980; Kinnear et al. 2002). Also, secondary poisoning of foxes occurred historically as a result of 1080 (sodium fluoroacetate) baiting for rabbit control in surrounding areas, and this reduced fox abundance (Christensen 1980; Kinnear et al. 2002). Relictual populations of woylies remained in these two reserves until the early 1970s (Sampson 1971) but following the effective use of the myxoma virus during the 1970s, and the subsequent reduced use of 1080 for rabbit control, fox control through secondary poisoning decreased significantly (King et al. 1981). The trap success

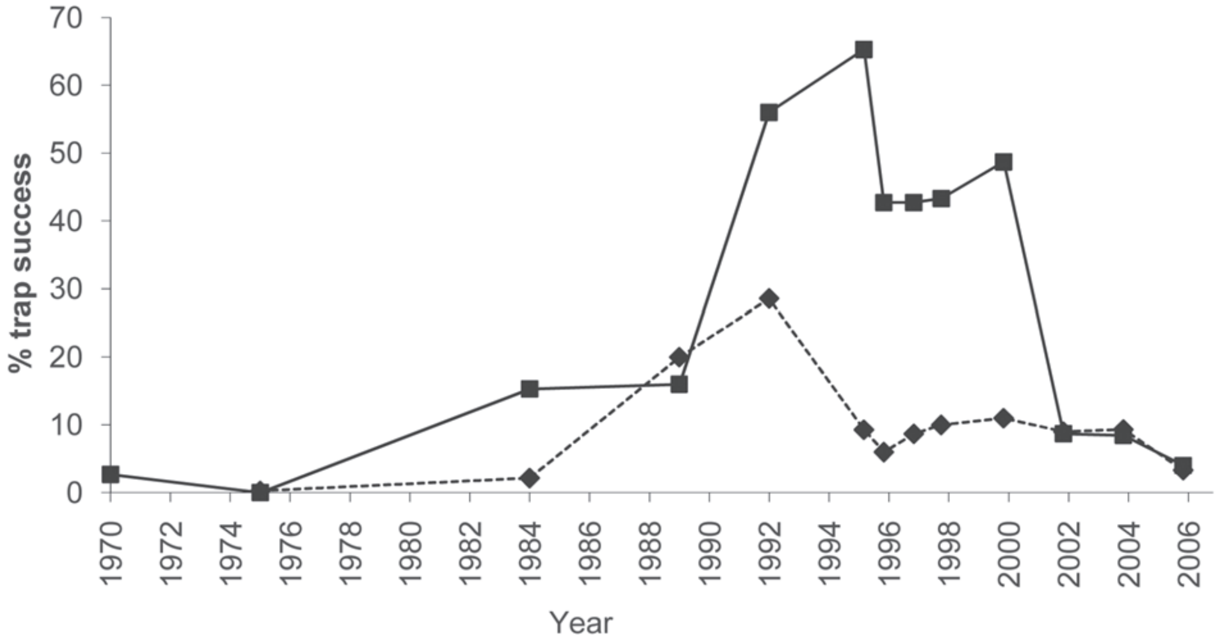

Figure 1. Woylie trap success in Dryandra Woodland (continuous line) and Tutanning Nature Reserve (dotted line) from pre-1980 to 2006 (data collected by personnel from the Department of Parks and Wildlife and earlier agencies).

of woylies in DW and TNR subsequently declined, and by the mid–late 1970s was virtually zero (Kinnear et al. 2002).

When regular fox baiting was initiated in DW and TNR in the early 1980s, the woylie populations increased once again (Kinnear et al. 2002; Fig. 1). Fox control continued and woylie trap success increased sufficiently, in these and other sites, for the species to be removed from the state, national and international threatened species lists in 1996 (Groom 2010). In that year the Western Shield Fauna Recovery Program was also initiated (Possingham et al. 2004), with fox predation being recognised as the main threat to many species of small- to medium-sized fauna (Wyre 2004). The regular delivery of fox baits containing 1080, to which fauna have a natural tolerance (King et al. 1981), was increased to 3.5 M ha. Despite maintained fox control, woylie trap-success declined in TNR after 1992 and in DW in 2000, and returned to pre-baiting levels. The reasons for these declines were unclear and were investigated in a four-year study that ran from April 2006 to November 2009 (Marlow et al. 2015a, 2015b).

The diet of foxes in DW and TNR was investigated as part of the larger study and the current consumption of woylies and other endemic fauna was determined. The foxes' diet in these baited reserves was compared with those in two unbaited sites, Quinns block (QB) and Highbury block (HB), and seasonal variations were examined. If woylies or other fauna were ingested more frequently at certain times of the year this may indicate a requirement to intensify fox control at those times if baiting was inadequate. Also, the ingestion of woylies, rabbits and brush-tail possums (*Trichosurus vulpecula*) during each season was compared with concurrent indices of their field availabilities to determine if these species were ingested in proportion to their abundance. If any of these species was being ingested disproportionally to its field abundance, this may suggest that foxes were exhibiting a preference for this species.

The diet of foxes was examined in relation to theoretical predator–prey models to obtain an explanation of how fox predation may have caused the decline of vulnerable prey species such as woylies in the past. In particular, the role of rabbits in the diet of foxes was examined because when rabbits are numerous, foxes may rely on these as their primary prey (Newsome et al. 1989). Rabbit populations can reach very high densities (Johnson 2006), and this enables fox populations to also reach high densities, with a resulting high ratio of foxes to endemic mammals (Johnson 2006). While rabbits are demographically resilient to high intensities of fox and feral cat (*Felis catus*) predation, woylies are less resilient because they are only able to produce three joeys per year (Serventy 1970). Other native species that have a higher reproductive rate than woylies may be able to better withstand fox predation but few marsupials have a reproductive output that rivals that of rabbits (Van Dyck & Strahan 2008).

METHODS

The study was undertaken at four sites: two baited sites (DW and TNR) and two unbaited sites (QB and HB). The main block of DW is a 12,000 ha bushland remnant 25 km north-west of Narrogin in the Wheatbelt of Western

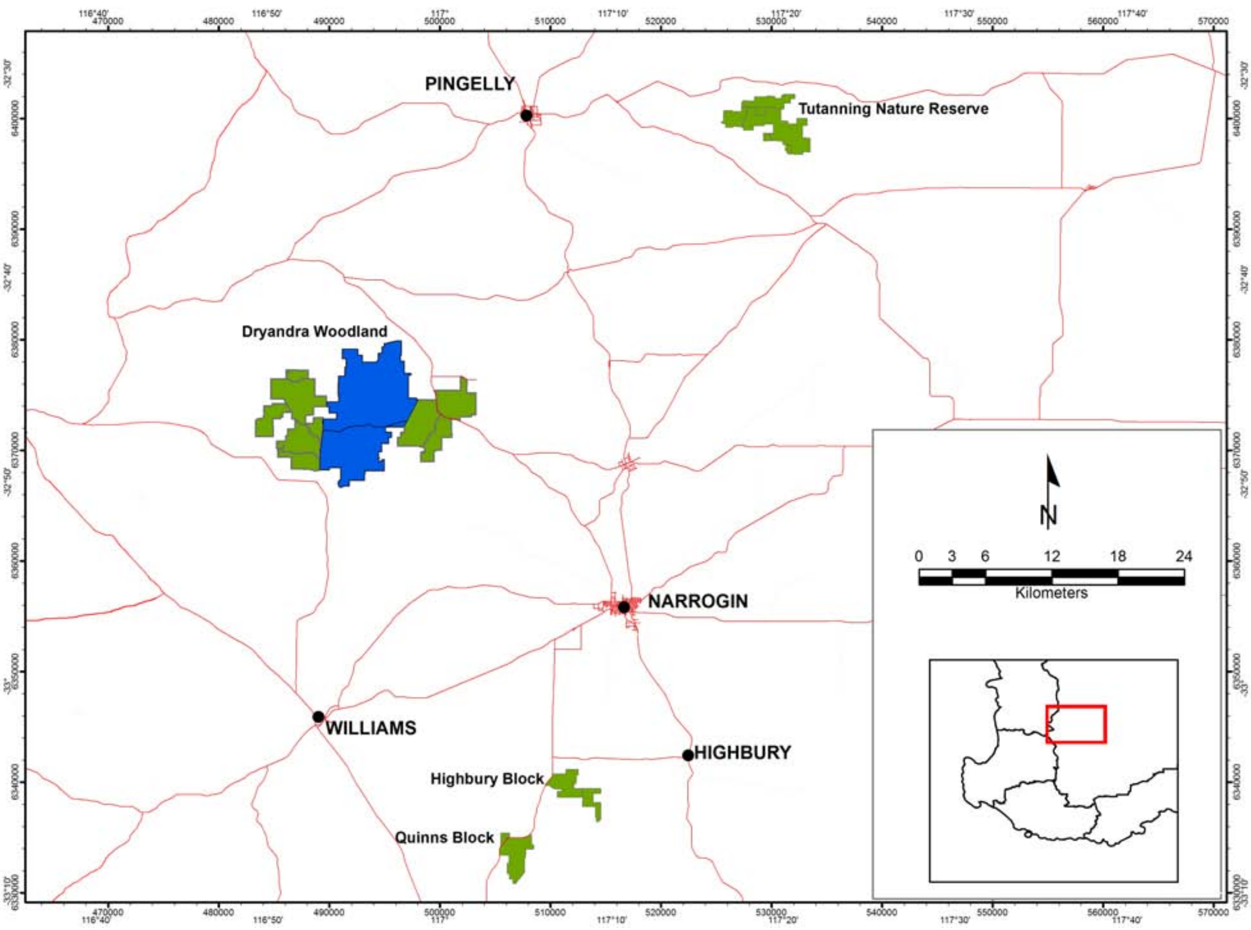

Figure 2. Map of the study sites. The blue area indicates the study site within Dryandra Woodland.

Australia. The study site was a 6800 ha area within the centre of the main block (Fig. 2). TNR is a small (2000 ha) reserve approximately 50 km to the north-east of DW. Both sites are baited monthly for fox control (12 times per year) with 3.0 mg 1080 meat baits. The nominal bait delivery rate is 5 baits km^{-2} (Thomson & Algar 2000). Dried meat baits (DMBs) sourced from the Department of Agriculture and Food, Western Australia (DAFWA) at Forrestfield were used in both sites from March 2006 to August 2008. From September 2008 to November 2009 the bait type used in DW was changed to Pro-baits, which were manufactured at the Department of Parks and Wildlife's bait factory at Harvey. In TNR, DMBs were used throughout the study.

In DW and TNR, the mammalian species present includes woylies, numbats (*Myrmecobius fasciatus*), bilbies (*Macrotis lagotis*), red-tailed phascogales (*Phascogale calura*), brush-tail possums (*Trichosurus vulpecula*), honey possums (*Tarsipes rostratus*), western pygmy-possums (*Cercartetus concinnus*), mardos (*Antechinus flavipes*), tammar wallabies (*Macropus eugenii*), brush wallabies (*M. irma*), western grey kangaroos (*M. fuliginosus*) and echidnas (*Tachyglossus aculeatus*). Quenda (southern brown bandicoots, *Isoodon obesulus*) were reintroduced into TNR between 1991 and 1995 and became naturally re-established in DW during the study. Chuditch (*Dasyurus geoffroii*) also naturally recolonised both sites during the study. Other fauna of interest due to their possible susceptibility to fox predation include the mallee fowl (*Leipoa ocellata*) and the carpet python (*Morelia spilota*). Foxes still occur in both sites, though their abundance is significantly reduced when compared with unbaited sites (Marlow et al. 2015a, 2015b). Feral cats also occur in both sites and their abundance is higher than in unbaited sites (Marlow et al. 2015a).

The two unbaited sites, QB and HB, are located approximately 25 km south-west of Narrogin and are each approximately 1000 ha in area. The fauna in these two sites was less intact with woylies, numbats, tammar wallabies and bilbies all being locally extinct. Brush-tail possums, brush wallabies, western grey kangaroos and echidnas still occur. Foxes were in higher abundance here than in the baited sites and feral cat densities were lower (Marlow et al. 2015a).

Fox scats were collected each season from March 2006 to September 2009 from predetermined 20 km transects and from sand-plots. Sand-plots were established throughout all four study sites at 500 m intervals along all tracks. They were constructed by removing 8–10 cm of the track surface and replacing the extracted material with sand. Each plot was approximately 1 m wide and extended across the track. One hundred and twenty nine sand-plots were positioned in DW, 75 in TNR, 31 in QB and 32 in HB. Sand-plots were monitored for three consecutive nights, both before and after a fox-baiting event, in each season. Foxes regularly deposited scats on freshly raked sand-plots. Two hundred and eighty-three scats were collected from DW and TNR and 167 from QB and HB.

All scats were sent to Scats About (www.scatsabout.com) and their contents were analysed. Scats were placed in individually labelled paper bags and oven-dried at 100 °C for 12 hours to kill parasite eggs. Samples were then placed in individual fine weave nylon bags and washed in a washing machine for approximately 15 minutes (Johnson & Alred 1982). Dietary components were identified to the lowest possible taxonomic class through comparison with known reference material or from published descriptions (e.g. Triggs & Brunner 2002; Watts & Aslin 1981). Hair samples were identified using the technique described by Brunner & Coman (1974). The percent volume of each prey item within the scat was visually estimated using a grid system within the sorting tray. The actual consumption of each prey item was approximated using digestibility estimates and the methods described by Lockie (1959). The digestibilities of rabbits (34.0), small mammals (18.2), reptiles (18.0) and small birds (20.0) were obtained from, or modified from, Lockie (1959). Carrion (50.0) and invertebrate (10.0) digestibility estimates were modified from Goszczynski (1974). All remains from western grey kangaroos and sheep were assumed to have been consumed as carrion because these species are generally too large to be live prey for foxes. Some juveniles of these species may have been killed and eaten by foxes but differentiating their consumption from that of adults was beyond the scope, and was not the focus, of this study.

The field abundances of woylies, rabbits and brush-tail possums were crudely estimated by calculating the proportion of sand-plots visited by each species on each day of monitoring. This was averaged for the six monitoring days each season. No field availability estimates were made for house mice, carrion, wallabies, birds, reptiles or invertebrates. The limited value of indices in reflecting abundance accurately is acknowledged (Anderson 2003).

The seasonal variability in the diet of foxes was examined using two-way analysis of variance for baited and unbaited sites, respectively. The amount of each dietary category that was calculated to have been consumed by foxes, after digestibility estimates had been applied, was used in these analyses.

The prey preferences that foxes exhibited for rabbits and possums were investigated by regressing the amount of each species calculated to have been consumed by foxes in each season against the index of field availability of that species for that season. A high *R* value was assumed to indicate a strong prey preference. We acknowledge that availability and consumption were measured using different techniques, and that the indices of availability may not be directly proportional to actual abundance. These limitations precluded a multivariate analysis of the data.

RESULTS

The main components of the foxes' diet were introduced species and carrion (Fig. 3). In baited sites foxes mainly consumed house mice (28%), carrion (sheep and western grey kangaroos, 26%), and rabbits (17%). In unbaited sites, foxes mainly ate carrion (sheep, 60%) and, to a limited extent, invertebrates (13%). Approximately 10% of the foxes' diet consisted of brush-tail possums, and <5% was from birds and <2% was from reptiles. In baited sites, 4% of the foxes' diet consisted of tammar and brush wallabies. Only one scat contained any identifiable woylie remains and this was collected from DW. No remains from numbats, bilbies, red-tailed phascogales, honey possums, western pygmy-possums, mardos, quenda, chuditch, echidnas, the mallee fowl or carpet pythons were detected. Three scats from DW and one scat from TNR contained feral cat remains.

There was no significant seasonal variation in the diet of foxes in both baited ($F_{3, 35} = 0.14$, p = 0.94) and unbaited sites ($F_{3, 35} = 0.13$, p = 0.98; Fig. 4). A strong prey preference for rabbits was detected in both baited and unbaited sites ($R^2 = 0.95$ and $R^2 = 0.91$ respectively; Fig. 5). Foxes did not show a strong preference for brush-tailed possums ($R^2 = 0.41$ baited sites and $R^2 = 0.30$ unbaited sites; Fig. 6) but similar quantities of possum were consumed in baited (12%) and unbaited sites (9%), despite there being fewer possums available in unbaited sites. Foxes consumed considerably fewer woylies than would be expected from the estimated field availability of this species in baited sites (Fig. 7). No woylies were present in unbaited sites.

DISCUSSION

The main components of the diet of foxes in the two baited Wheatbelt reserves were house mice, carrion (sheep and western grey kangaroos) and rabbits. In the two unbaited sites, foxes mainly ate sheep carrion and a limited quantity of invertebrates. These results are consistent with those obtained from many other studies where introduced species and carrion were observed to be the main components of the foxes' diet (e.g. Croft & Hone 1978; Catling 1988; Molsher et al. 2000; Read & Bowen 2001; Saunders et al. 1995, 2004). Previous observations that foxes are opportunistic predators/scavengers with a wide range of dietary items were reconfirmed.

The main endemic mammal to be consumed by foxes was the brush-tail possum and this constituted approximately 10% of the diet in all sites. A lesser amount of tammar and brush wallabies was consumed by foxes in baited areas. The consumption of these native mammals in baited areas is consistent with the results of Kinnear et al. (1988, 1998), Paltridge (2002), Pavey et al. (2008) and Cupples et al. (2011), who all found that when foxes are controlled the proportion of endemic species in their diet increases. However, this observation contrasts with the results of Roberts et al. (2006), who did not observe increased consumption of endemic species in baited sites

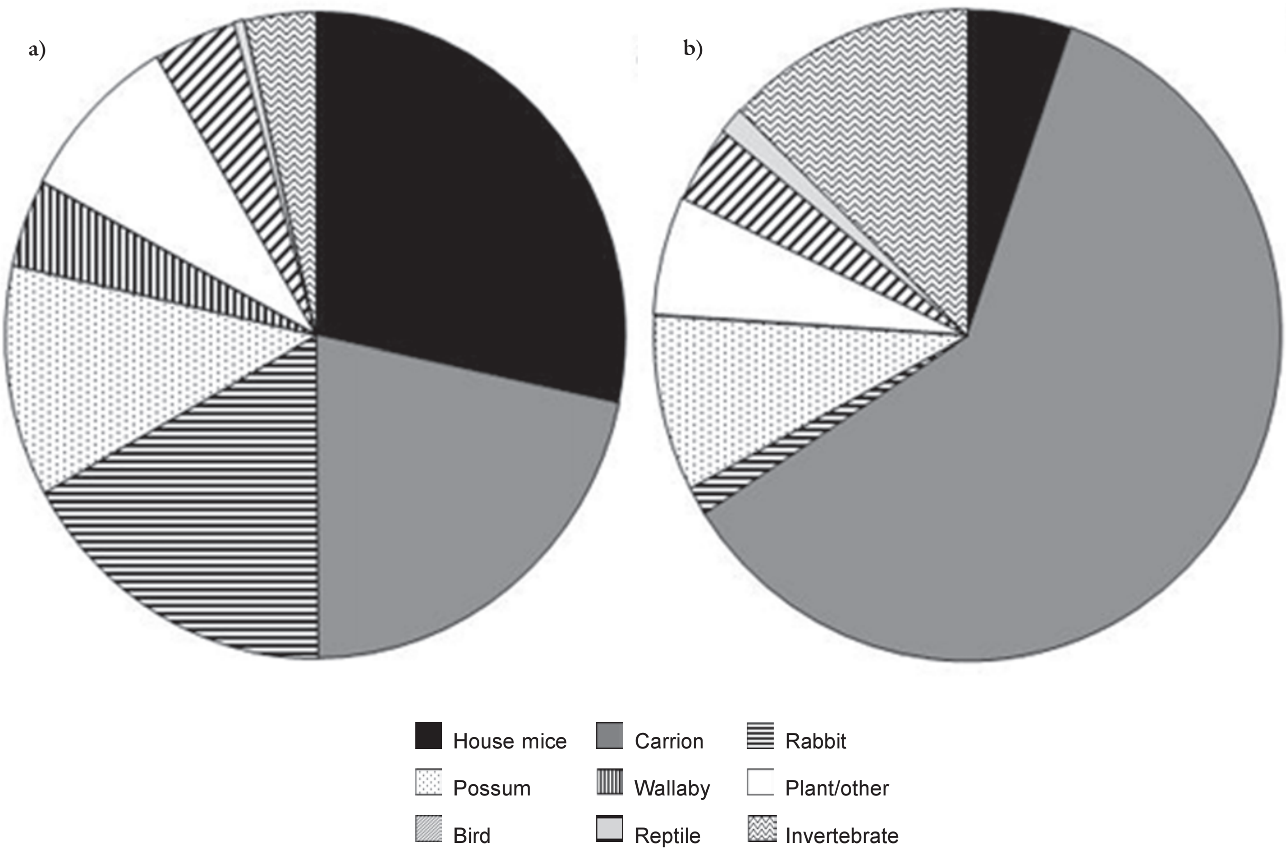

Figure 3. Overall composition of the diet of foxes in a) baited sites (N = 283) and b) unbaited sites (N = 167).

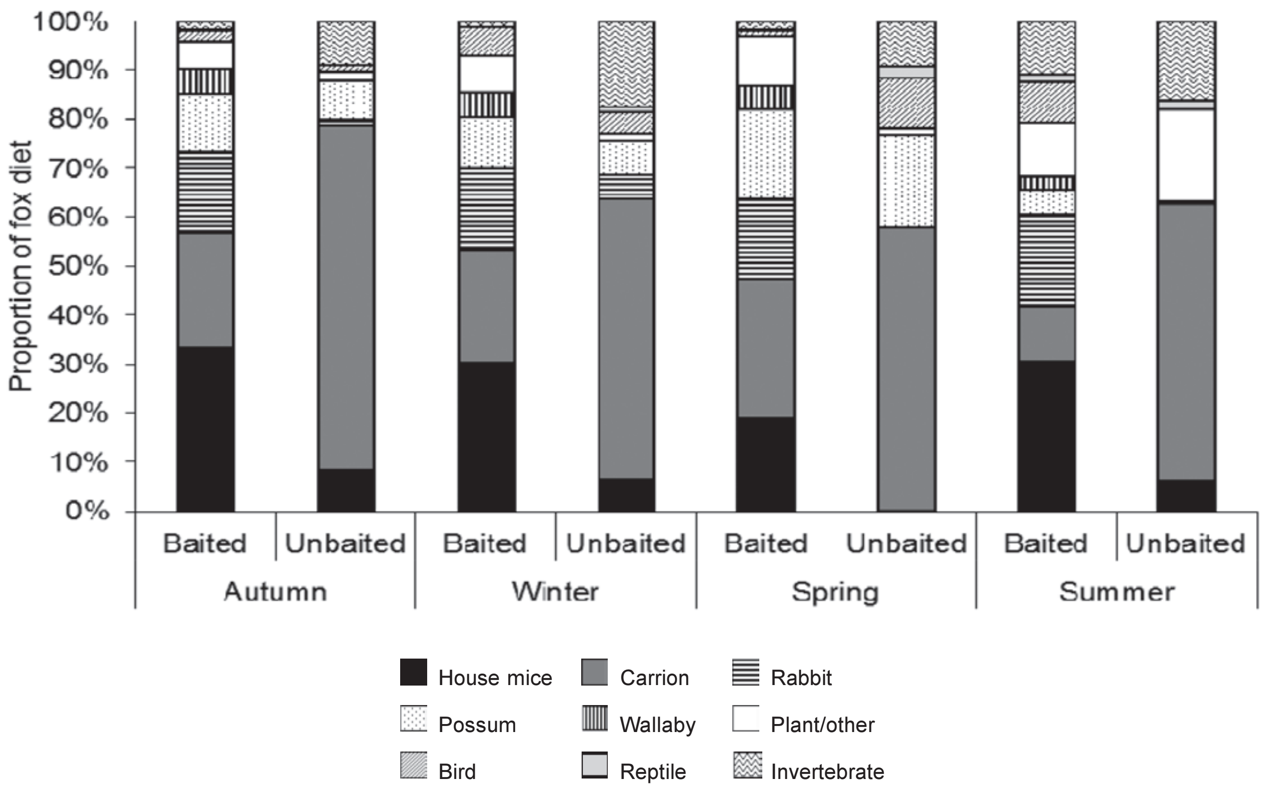

Figure 4. Seasonal composition of the diet of foxes in baited and unbaited sites.

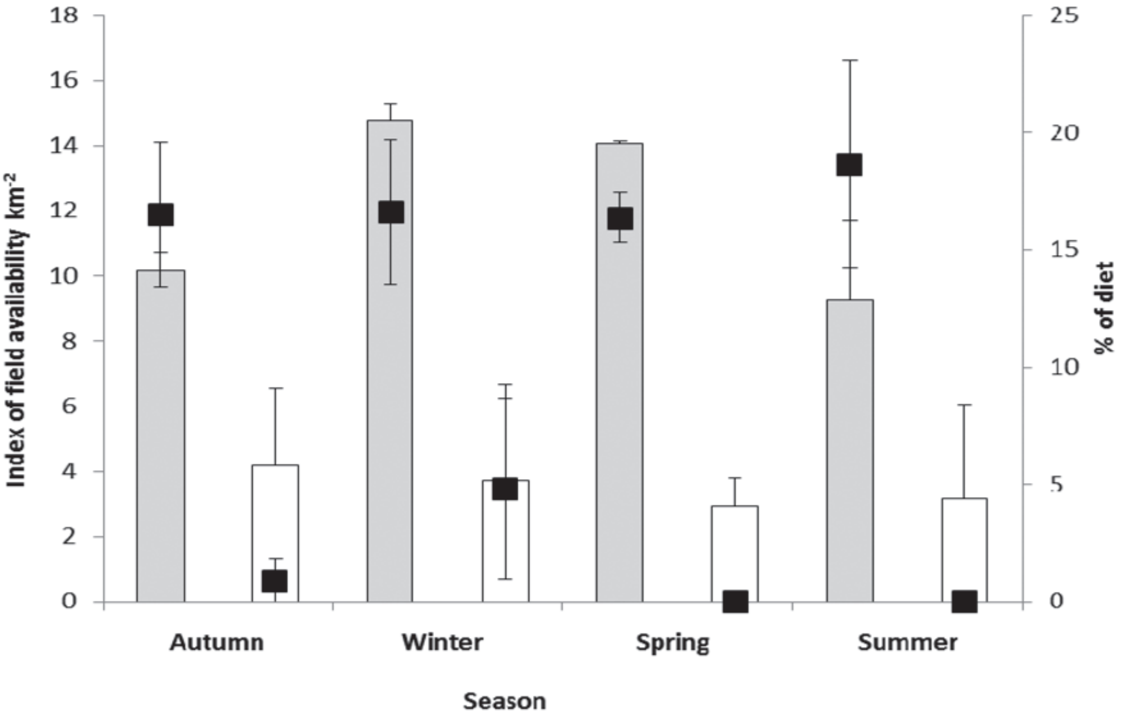

*Figure 5. Seasonal dietary occurrence and indices of field abundance of rabbits (*Oryctolagus cuniculus*) in baited and unbaited sites. Bars show indices of availability ± SE (baited sites, closed bars; unbaited sites, open bars); black squares show dietary occurrence ± SE.*

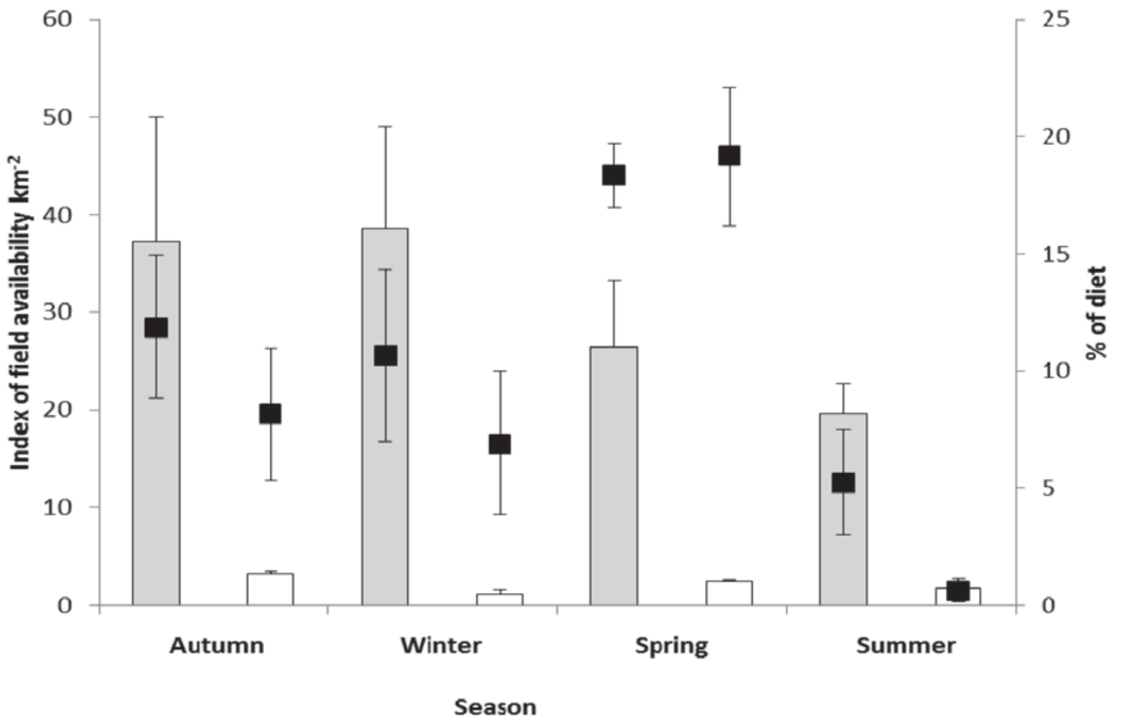

*Figure 6. Seasonal dietary occurrence and indices of field abundance of brushtail possums (*Trichosurus vulpecula*) in baited and unbaited sites. Bars show indices of availability ± SE (baited sites, closed bars; unbaited sites, open bars); black squares show dietary occurrence ± SE.*

but the results of that study are equivocal because they had no unbaited control sites.

Foxes consumed very few threatened mammals or other small vertebrates. Numbats, chuditch, red-tailed phascogales, bilbies and quenda were not detected in scats, and birds and reptiles were of little dietary importance. Virtually no woylie remains were observed and only one scat containing any woylie material was collected. Woylies were not consumed in proportion to their field availability and this observation may be explained if they eluded predators and used *Gastrolobium* thickets as predation refuges (Christensen 1980; Kinnear et al. 2002). It may

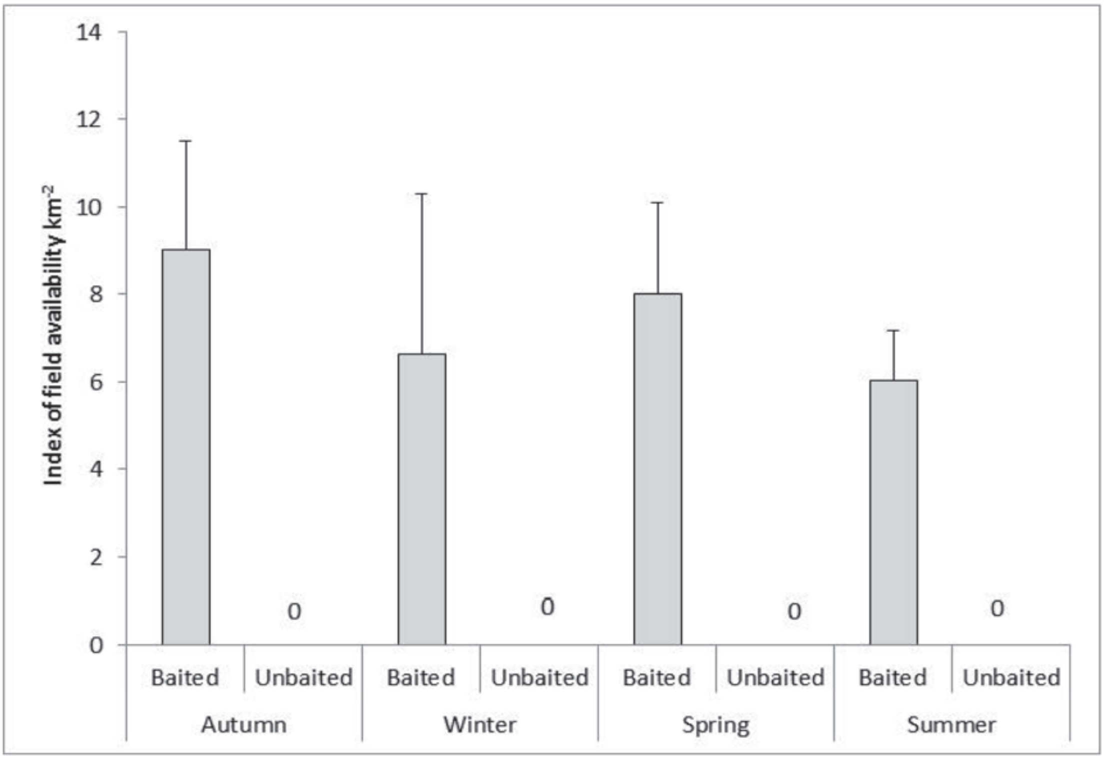

*Figure 7. Seasonal field abundance (± SE) of woylies (*Bettongia penicillata*) in baited sites. (No woylies were present in unbaited sites.)*

also be explained if the indices of field abundance were overestimates of the actual population density or if more predation occurred than was detected from scats. During a concurrent study (Marlow et al. 2015a), 21% of radio collared woylies (N = 20) were killed by foxes. However, of these, 11 were not consumed by foxes and virtually the complete carcass was recovered. The analysis of the contents of fox scats may not therefore be a useful method of detecting prey preferences for rare species, or their presence in a site, despite its use being advocated by Brunner et al. (1976).

There was no significant seasonal variation in the diet of foxes in baited areas and therefore there is little evidence that fox baiting needs to be intensified at any specific time when endemic fauna may be more vulnerable to predation. The current fox-baiting regime in DW and TNR appears to be maintaining foxes at lower densities than in the unbaited sites and so no alteration to the baiting regime is required at present (Marlow et al. 2015b).

A high correlation between the consumption of rabbits and indices of their field availability was observed and suggests a strong prey preference for this species. A similar high incidence of rabbits in the diets of foxes in conservation areas where endemic species also occur has been observed in other studies. Seebeck (1978) observed a high occurrence of rabbits but an extremely low incidence of the long-nosed potoroo (*Potorous tridactylus*) and other native fauna remains in fox scats collected in the Ralph Illidge Sanctuary east of Warnambool, Victoria. Similarly, Lunney et al. (1990) found rabbits were a major component of the diet of foxes in a state forest and in national park areas near Bega, New South Wales, but that long-nosed potoroos, long-nosed bandicoots (*Perameles nasuta*) and brush-tail and ringtail possums (*Pseudocheirus peregrinus*) were rarely detected in fox scats.

The impact of fox predation on rabbits and endemic fauna has been theoretically modelled by Pech et al. (1992, 1995), Pech and Hood (1998) and Sinclair et al. (1998). Their models include two forms of the functional response which correspond to the differing susceptibilities of prey to fox predation at low prey densities. A Type II functional response occurs when a primary prey species such as rabbits is vulnerable to fox predation at all densities and has no refuge at low densities. In contrast, a Type III functional response is an S shaped curve which occurs when the foxes' main prey species is able to avoid predation at low densities but predation increases with density above a certain threshold (Sinclair et al. 1998; Pech & Hood 1998). Although a strong dietary preference for rabbits by foxes was observed in this study, insufficient data were collected to enable a differentiation between the presence of a Type II or a Type III functional response between foxes and rabbits. However, previous modelling of the interactions between foxes and rabbits has suggested a Type III functional response is most likely (Sinclair et al. 1998). A sub-set of these theoretical predator-prey models specifically investigates the impacts of foxes on endemic species when rabbits are the primary prey of foxes and these are reduced in density (Sinclair et al. 1998). These models predict that when a rabbit population crashes and foxes are suddenly short of food, they can inflict considerable predation pressure on endemic species and drive them to extinction (Sinclair et al. 1998). This phenomenon is termed hyperpredation (Smith & Quin 1996) and this, in conjunction with surplus killing (Short et al. 2002), may have been resulted in faunal declines in Australia.

Sinclair et al. (1998) discuss several management actions which may be undertaken to transform the functional response of foxes and rabbits so that at low densities vulnerable prey species such as woylies are not driven to extinction. These management options could be implemented in conservation estate in Western Australia and elsewhere to minimise the risks to threatened fauna from the presence of rabbits and a sudden decrease in their density. Sinclair et al. (1998) recommend undertaking habitat manipulation so that vulnerable species have more refuges from predators. The importance of suitable habitat structure in reducing the risk of fox predation to various prey species has been observed in several other studies (Stokes et al. 2004; Pickett et al. 2005; Strauß et al. 2008) and, as stated above, the presence of *Gastrolobium* thickets maybe one of the factors explaining the continued presence of woylies in DW and TNR (Christensen 1980; Kinnear et al. 2002). Burrows et al. (1987) recognised that *Gastrolobium* thickets in DW had become sparse due to senescence caused by prolonged fire suppression, and recommended the strategic burning of patches of vegetation infrequently every 20–60 years to maximise biodiversity outcomes. These goals are reflected in the current Dryandra Woodland Management Plan (Department of Environment and Conservation 2011), which attempts to increase thicket development to maximise habitat availability for fauna.

Sinclair et al. (1998) also suggest removing rabbits from the habitat of threatened species, such as the woylie, as they theorise this will reduce fox density and thus reduce predation on these species at low densities. Fox densities may decline rapidly when rabbits decline (Read & Bowen 2001; Holden & Mutze 2002) but a protracted lag phase may occur if foxes preferentially prey on rabbits despite their densities being reduced (Saunders et al. 2004). However, fox density may not always decrease even if rabbits are effectively removed (e.g. Edwards et al. 2002) due to the presence of other food items that may sustain the fox population. In some areas of conservation estate where rabbit densities are naturally low or have been reduced the main components of the foxes' diet are small- to medium-sized mammals (Triggs et al. 1984; Glen et al. 2006).

The final management option recommended by Sinclair et al. (1998) is the reduction of predator densities. Sinclair et al. (1998) recognised the effectiveness of fox baiting in the conservation of woylies and other vulnerable prey species and recommended removing predators to alter the dynamics between predators and prey and to thus increase the survival of threatened endemic species. The removal of foxes at DW and TNR appears to be occurring adequately under the current baiting regime, because fox densities are significantly lower in baited sites than in unbaited sites (Marlow et al. 2015b). However, feral cats were observed to be the main predator of woylies in DW and TNR and accounted for 65% of woylie mortalities (Marlow et al. 2015a). Feral cat control methods need to be integrated with current fox baiting programs so that effective and efficient control of both introduced predators is achieved (Moseby et al. 2009; Berry et al. 2012). If predation by introduced predators can be reduced through the removal of rabbits, by direct control and through habitat augmentation by fire, woylies and other endemic threatened species in fragmented Wheatbelt sites and elsewhere may recover to their earlier abundances.

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The development of a toxic 1080 bait, Pro-bait, for fox (*Vulpes vulpes*) control in Western Australia

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ABSTRACT

The *Western Shield* fauna recovery program delivers fox (*Vulpes vulpes*) baits containing 1080 (sodium fluoroacetate) to approximately 3.4 million ha at least four times each year. Originally dried meat baits (DMB) produced by the Department of Agriculture and Food Western Australia (DAFWA) were used but in 1998 the Department of Parks and Wildlife (then Conservation and Land Management [CALM]) developed a new fox bait, Pro-bait, to reduce baiting costs. Pro-baits needed to have similar uptake by foxes and field longevity to DMBs if they were to achieve comparable levels of control. These characteristics were tested between 1999 and 2004 in an experiment that had four phases. In the first phase, uptake of Pro-baits and DMBs by foxes was compared in a field trial and foxes were observed to be 11% less likely to ingest Pro-baits than DMBs (n = 178). This was postulated to be due either to bait damage by invertebrates or to lower Pro-bait acceptability. In Phase 2, invertebrate damage to six bait types (standard Pro-baits, a Pro-bait with added invertebrate repellent Coopex®, a hard Pro-bait, a hard Pro-bait with added Coopex®, DMBs and Foxoff baits) was compared at four sites, and DMBs suffered the most damage. To increase the acceptability of Pro-baits, fox uptake of six flavour enhancers (hexylamine, ethyl caproate, monosodium glutamate or commercial beef, chicken and honey flavours) was examined during Phase 3, and the chicken flavour was most favoured. Accordingly, in Phase 4, the chicken flavour was added to the Pro-bait recipe and field uptake by foxes of DMBs and reformulated Pro-baits was compared. The uptake of both bait types was 87% (n = 104). Collectively, these trials demonstrated that Pro-baits are as efficacious as DMBs in controlling foxes in Western Australia. Pro-baits were registered for use in Western Australia by the Australian Pesticides and Veterinary Medicines Authority (APVMA) in 2002. In late 2005, the Department's Corporate Executive officially endorsed the use of Pro-baits for use in *Western Shield* fox control operations.

Keywords: bait development, fox, introduced predator control, *Vulpes vulpes*, 1080

INTRODUCTION

The rate of mammalian extinction and decline in Australia is higher than that of any other country (Short & Smith 1994). Many of these faunal declines occurred after European foxes (*Vulpes vulpes*) were introduced into Victoria in the mid–late 19th century and as they colonised much of southern half of the continent (Abbott 2011). There is considerable anecdotal and circumstantial evidence to suggest that fox predation was a major factor in the declines and this has been recognised nationally as a key threatening process (Department of Environment, Water, Heritage and the Arts 2008). Foxes can be controlled through the regular delivery of meat baits containing the poison 1080 (sodium fluoroacetate; Saunders & McLeod 2007). The use of this poison is very appropriate because introduced predators such as foxes and cats are highly sensitive to it, whereas many species of native fauna have a natural tolerance to it, especially in south-west Western Australia (King et al. 1981). 1080 baiting is currently used in several large-scale and numerous smaller-scale fox-control programs throughout Australia for both conservation and agricultural purposes (Saunders & McLeod 2007; Robley et al. 2014).

Fox control commenced in several small Wheatbelt reserves in Western Australia in the 1980s (Kinnear et al. 2002) and this resulted in the recovery of a number of species of mammals including numbats (*Myrmecobius fasciatus*; Friend 1990) and rock wallabies (*Petrogale* *lateralis*; Kinnear et al. 1988, 1998). In 1996 the area in which fox control was undertaken was expanded to approximately 3.5 million ha when the Department of Parks and Wildlife (then the Department of Conservation and Land Management [CALM]) initiated its *Western Shield* fauna recovery program (Possingham et al. 2004). This program relies on the repeated delivery of 1080 meat baits at least four times (Armstrong 2004), and ideally six times (de Tores & Marlow 2012), per year to be effective. Baiting to control foxes in Western Australia has been so successful that three species, the woylie (*Bettongia penicillata*), the tammar wallaby (*Macropus eugenii*) and the quenda (or southern brown bandicoot, *Isoodon obesulus*), were removed from the state's threatened species list (Mawson 2004).

The fox bait used in Western Australia during these fauna recoveries was the dried meat bait (DMB), manufactured by Department of Agriculture and Food Western Australia (DAFWA). DMBs are made from a single piece of kangaroo meat and are highly attractive and palatable to foxes (Thomson & Algar 2000). Given the quantity of baits used each year in the *Western Shield* fauna recovery programme, replacing the relatively expensive DMB with a more economical alternative was thought likely to yield significant savings in delivering the program (Armstrong 2004). In 1998, CALM decided to reduce the program's baiting costs by developing a new sausage-style fox bait, Pro-bait, based on a salami manufacturing process (Armstrong 2004). The advantages of this development were an automated process, large economically effective production runs, minimal wastage and improved shelf-life of baits. The uniform shape and size of the new bait type also improved packaging efficiency and reduced transport and storage costs (Armstrong 2004).

Before the highly successful DMB could be replaced operationally with Pro-baits, the new bait type had to be shown to be as effective at controlling foxes. It was essential that Pro-baits were equally attractive to foxes in the field so that they would be found and ingested, and similar levels of control attained. Pro-baits needed to be highly palatable so that foxes would consume them readily and not cache them (van Polanen Petel et al. 2001). Pro-baits also needed to have similar field longevity characteristics to those of DMBs. In the field, baits may deteriorate if they are damaged by invertebrates or if they are exposed to soil moisture or rain (McIlroy et al. 1988; Twigg et al. 2000; Twigg & Socha 2001). DMBs are able to withstand some invertebrate damage and weathering because they are partially dried during manufacture and develop a protective outer skin or crust (Thomson1986; Kinnear et al. 2010). Pro-baits required a similar or greater capacity to withstand damage because if they deteriorated more rapidly than DMBs foxes may not have time to find them, and thus their efficacy in controlling foxes would be reduced.

Before Pro-baits could be used operationally their risk to non-target species had to be assessed to ensure that baits delivered to control foxes did not detrimentally impact the populations of threatened species they were intended to protect. Although many non-target species are tolerant to 1080 (King et al. 1981), smaller animals may be susceptible to poisoning if they consume a bait containing sufficient 1080 to kill a 5–8 kg fox. The hard crust on DMBs decreases the ability of smaller, non-target species to chew on the bait, thus reducing the ingestion of bait material and 1080 (Calver et al. 1989). Pro-baits would need to be similarly resistant if they were to withstand chewing by non-target species.

METHODS

Bait manufacture

Pro-baits are sausage baits that contain 70% minced kangaroo meat, 20% animal fat (pork or chicken) and 10% canine 'digest' (a commercial flavour enhancer for dog food). A salami-style binder is added to this mixture to promote hardening of the final product so that weathering and the risk of non-target consumption of the bait is reduced. When manufactured, individual Pro-baits weigh approximately 80–85 g and they are then heated to between 30–40 °C to promote uniform shrinkage during the drying process. Baits are dried to approximately 40 g before delivery to the field (Armstrong 2004). Pro-baits are manufactured in a purpose-built factory that was constructed at Harvey WA (Armstrong 2004).

Phase 1: An initial comparison of the field uptake of Pro-bait and DMB by foxes

The acceptability of Pro-baits to foxes was examined by comparing the relative uptake of Pro-baits and DMBs at two sites in the semi-arid zone of WA. The study sites were Wagga Wagga Station, a pastoral lease in the Yalgoo region, and Burnabinmah Station, a former pastoral lease that is now conservation estate in the Paynes Find region (Fig. 1).

The two bait types were labelled with different biomarkers so that foxes ingesting either bait could be identified. The biomarkers iophenoxic acid (IPA; Sigma-Aldrich, Castle Hill NSW) and tetracycline HCl (Sigma-Aldrich, Castle Hill NSW) were used. IPA raises blood iodine levels and its ingestion can be detected by analysing a blood sample (Saunders et al. 1993). If the blood iodine level present in a fox was above a prescribed background level it was assumed that an individual had ingested a bait. IPA was added to baits as a solution prepared by dissolving IPA crystals in 100% alcohol. A 0.6 ml aliquot of the solution contained 20 mg of IPA, and this volume was added to each bait using a standard dosing gun. After dosing, the baits were kept upright as they dried and the IPA remained in the baits as they cured. Tetracycline produces a characteristic fluorescent ring in the canine teeth of foxes that ingest it (Johnston et al. 1987). Tetracycline was added to baits as a powder using a modified syringe to insert 150 mg of tetracycline powder into a 2 mm diameter hole that had been drilled into the side of each bait with an electric drill. To ensure that

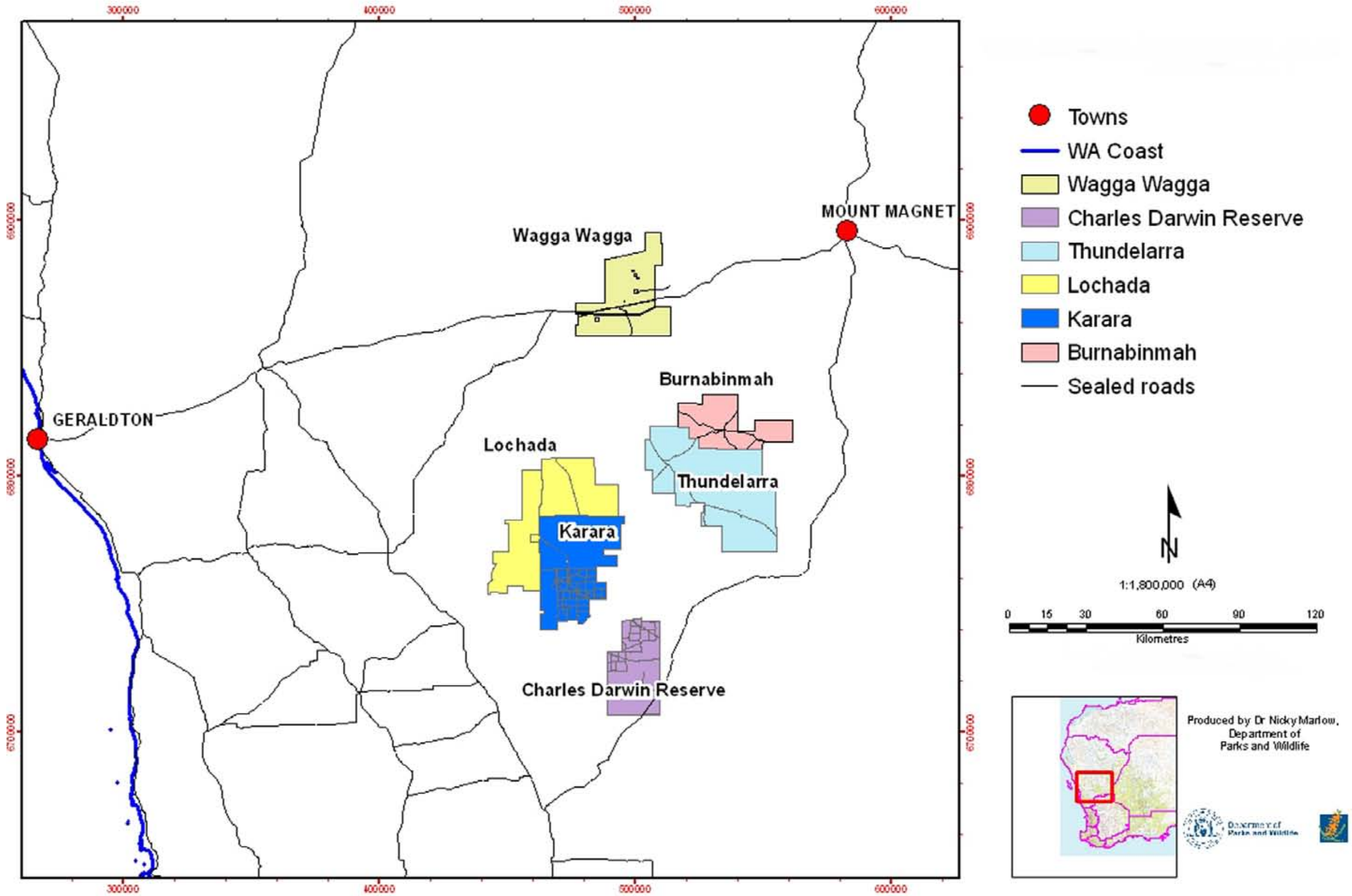

Figure 1. Map of the bait development study sites.

tetracycline was an effective biomarker, a sample of seven captive foxes were fed non-toxic tetracycline labelled baits. These foxes were euthanased with cyanide 16 days after they had ingested a bait. Very thin sections of each of the fox's canine teeth were produced using an Isomet saw. These sections were examined under a microscope using ultraviolet light (450 nm) to reveal the presence of fluorescent rings that indicated bait consumption. Examination of the teeth of all foxes detected tetracycline rings.

Non-toxic Pro-baits and DMBs labelled with biomarkers were aerially delivered to both study sites at the standard baiting rate of 5 baits km^{-2} (i.e. a combined total of 10 baits km^{-2} were laid) with the expectation that 80–95% of foxes would ingest baits (Thomson & Algar 2000; Thomson et al. 2000). On Burnabinmah Station, DMBs were labelled with IPA and Pro-baits were labelled with tetracycline. To avoid any potential influence of the biomarker on bait uptake, the biomarkers were interchanged for the subsequent trial on Wagga Wagga station (i.e. Pro-baits were labelled with IPA and DMBs were labelled with tetracycline). The non-toxic baits were delivered to both sites on 15 October 1999. An area of approximately 200 km^{-2} was baited on each station and the position of the plane on the baiting transects when the baits were dropped was recorded using a GPS (model GPS76; Garmin Corporation, Kansas USA). Transects were approximately 1 km apart.

Foxes were given sufficient time to find and ingest baits (Dexter & Meek 1998; Thomson et al. 2000) and were then killed six to seven weeks after bait delivery using cyanide (Algar & Kinnear 1990). Cyanide baiting involved the placement of two wax capsules containing 1 g sodium cyanide at 200 m intervals along transects within the study site. Capsules were covered with a condensed milk/icing sugar lure. Foxes died at, or very close to, the site at which they had bitten a cyanide capsule and it was relatively easy to collect the carcasses. Cyanide transects of up to 20 km in length were positioned each night. Fox carcasses were retrieved early the following day and a blood sample and all canine teeth were collected from each fox. Blood samples were not centrifuged because they had been obtained from foxes that had been dead for up to 12 hours. Samples were stored frozen. The iodine concentration of the whole blood sample was obtained using the method described by Saunders et al. (1993). Hot perchloric acid was used to release the protein-bound iodine and in that process the iodine was oxidised to iodide, which catalysed a caesium-arsenic redox reaction. The change in absorbance (measured at 420 nm) was proportional to the iodide and consequently the total iodine concentration. Samples with concentrations higher than the standard ranges were diluted with deionised water and re-run. The background level iodine concentration of foxes for the study area was estimated from four foxes that were killed with cyanide just prior to bait delivery on 15 October 1999. An iodine concentration of more than three standard deviations above the mean value for the 'control' foxes was concluded to indicate that a fox had ingested a bait. The uptake of the two biomarkers, and hence the ingestion of the two bait types, was compared using chi-squared contingency tests.

Phase 2: The comparative testing of the field longevity of Pro-bait and DMB

A trial to compare the field longevity of standard Pro-baits and DMBs was conducted to assess whether decreased Pro-bait durability had resulted in the lower uptake of this bait type by foxes during the initial comparison in Phase 1. The longevity of four other bait types was also investigated: a Pro-bait with added invertebrate deterrent Coopex®; a Pro-bait dried to a hard consistency (drying continued until daily weight loss did not exceed 1% of bait weight); a hard Pro-bait with added Coopex®; and a commercially available fox bait (Foxoff; Staples et al. 1995). Non-toxic samples of each bait type were placed in exclosures to prevent non-target removal and were monitored at four sites with different mean annual rainfalls: Collie (200 km south-east of Perth, rainfall 940 mm), Kalgoorlie (600 km east-north-east of Perth, rainfall 265 mm), Manjimup (300 km south of Perth, rainfall 1010 mm) and Narrogin (190 km south-east of Perth, rainfall 500 mm). Baits were weighed to the nearest 0.1 g before being placed in exclosures on 14 February 2003. A random sample of four baits of each of the six types was collected after 1 day, 4 days, 7 days, and then weekly for 10 weeks. Baits were reweighed after collection and the proportion of each bait removed by invertebrates was calculated. The amount of each bait type removed by invertebrates in all sites for each time frame was averaged. A more detailed investigation of the site-related removal of DMBs during each time frame was undertaken using a two-way ANOVA. This analysis was repeated for the standard Pro-bait. The extent of invertebrate damage to Pro-baits within each time-frame was then compared with that of each of the other bait types using a series of two-way ANOVAS.

Phase 3: A field comparison of the uptake by foxes of six flavour enhancers

A variety of flavour enhancers was tested to determine if foxes showed any preferences. The preferred flavour could then be incorporated into Pro-baits to increase uptake. Six flavour enhancers were trialled: hexylamine (which smells like rotting meat), ethyl caproate (which smells like matured cheese), monosodium glutamate, a commercial beef flavour (Springarom beef juice #220, Magnum Essence Pty Ltd, Osborne Park WA), a commercial chicken flavour (50% Springarom chicken #221, Magnum Essence Pty Ltd, Osborne Park WA and 50% Chicken booster #9502 New Foods Coatings Pty. Ltd, Wetherill Park NSW), and a commercial honey flavour (Honey #576, Magnum Essence Pty Ltd, Osborne Park WA). Fox preferences for the flavours were compared by incorporating them into a lure placed on cyanide capsules. The lure was made from a puree of Pro-bait ingredients, minus any binder, plus the flavour enhancer (10 g kg^{-1}). Two capsules were placed at each cyanide station, one with a test lure and the other with a standard condensed milk and icing sugar lure. The lure on the cyanide capsule which killed the fox was assumed to be more appealing. If no fox was killed a preference was assumed if only one lure was removed. If both lures were removed no preference could be assigned. These trials were undertaken between 25 August to 5 September 2003 at Karara and Thundelarra stations in the pastoral area of WA where no recent fox control had been undertaken (Fig. 1). Standard cyanide transects were run each night with 100 bait stations per 20 km of transect. On each night only one test lure was compared with the standard lure. The order of lure testing was assigned randomly.

Phase 4: A field trial to compare the uptake of DMB and reformulated Pro-bait by foxes

After the preferred flavour enhancer had been identified in Phase 3 it was then added to Pro-baits (10 g kg^{-1}) in an attempt to increase their uptake to equal that of DMBs. The relative field uptake by foxes of the reformulated Pro-bait was then compared with that of DMBs at two sites in the semi-arid zone of WA: Lochada Station and Charles Darwin Reserve (CDR; Fig.1). Both bait types were aerially delivered to both study sites on 26 February 2004 at the standard baiting rate of 5 baits km^{-2} (i.e. a combined total of 10 baits km^{-2} were laid). An area of approximately 400 km^{-2} was baited at each site using the same methods as described above. Foxes were baited with cyanide at both sites six weeks later (13–23 March 2004) and their carcasses retrieved. On CDR, DMBs were labelled with IPA and Pro-baits with tetracycline. On Lochada Station, Pro-baits were labelled with IPA and DMBs with tetracycline. No recent fox control had been undertaken at either site.

To determine uptake of IPA-labelled baits, a further calculation of the mean background iodine concentration in the blood of foxes was made. Four foxes were killed with cyanide on CDR on 26 February 2004, just before the labelled baits were delivered. The IPA results obtained from these individuals were combined with those obtained during the 1999 trial.

RESULTS

Phase 1: An initial comparison of the field uptake of Pro-bait and DMB by foxes

Fifty-eight foxes were obtained from Burnabinmah Station and 78 from Wagga Wagga Station. The four foxes sampled for background iodine concentration in the study site before the baiting trials commenced had a mean blood iodine concentration of 13.1 ug L^{-1} (SD = 10.2). Foxes in the treatment samples that had a blood iodine concentration of more than 43.7 ug L^{-1} (i.e. mean + 3 SD) were determined to have ingested a bait. Three standard deviations greater than the mean (instead of two) were used because there were very few samples, and it was concluded that a Type II error was preferable to a Type I error (i.e. it was preferable to assume that too few foxes had ingested baits than to assume too many had). The concentration of iodine in the blood samples ranged from 0.36 to 24,959 ug L^{-1}.

The proportion of foxes that consumed each bait type within the study sites was not significantly different. At Burnabinmah, 81% of foxes ingested Pro-baits and 88% ingested DMBs, whereas at Wagga Wagga, 64% of foxes ingested Pro-baits and 78% ingested DMBs. However, when data were pooled across sites, the uptake of DMBs was significantly greater (82% compared with 71% for Pro-baits; $X^2 = 4.65$; $p < 0.05$).

Phase 2: The comparative testing of the field longevity of Pro-bait and DMB

Of all the bait types tested, DMBs suffered most from invertebrate damage (Fig. 2) and this increased at sites with higher rainfall ($F_{3,191} = 55.0$, $p < 0.001$). In contrast, there were no significant differences in invertebrate damage to the standard Pro-baits between sites. Also, Pro-baits were consumed significantly less by invertebrates than DMBs ($F_{1, 383} = 59.8$, $p < 0.001$). The addition of Coopex® to Pro-baits significantly decreased invertebrate damage, and both the standard Pro-bait with Coopex® ($F_{1, 383} = 19.9$, $p < 0.001$) and the hard Pro-bait with Coopex® ($F_{1, 383} = 20.4$, $p < 0.001$) withstood invertebrate damage significantly more than the standard Pro-bait. However, increasing bait hardness did not increase longevity and there was no significant difference in invertebrate damage between the standard Pro-bait and the hard Pro-bait. Foxoff baits sustained less invertebrate damage when compared with the standard Pro-bait during the first 11 monitoring periods ($F_{1, 351} = 9.9$, $p < 0.01$) but most Foxoff baits had either completely disintegrated or had deteriorated into an amorphous mass by the final monitoring period.

The invertebrate species responsible for the damage to baits varied between the four sites. At Collie and Manjimup most damage was done by beetle larvae (*Dermestes* spp.) and there were also dipteran eggs within the baits. The removal of bait material at Kalgoorlie and Narrogin was primarily caused by meat ants (*Iridomyrmex purpureus* and *I. chasei* respectively).

Phase 3: A field comparison of the uptake by foxes of six flavour enhancers

The carcasses of 38 foxes were recovered from Karara Station and 37 from Thundelarra Station. Whether the lure on the capsule these foxes had bitten contained the flavour enhancer or was the control was recorded (Table 1). When foxes removed only one lure from a pair of cyanide capsules, their preference for the flavoured or the control lure was assigned. This occurred on 110 occasions on Karara station and on 49 occasions on Thundelarra station. The only enhancer for which foxes had any significant preference was the chicken flavour (Table 1). In contrast, the flavours ethyl caproate and hexylamine were significantly avoided.

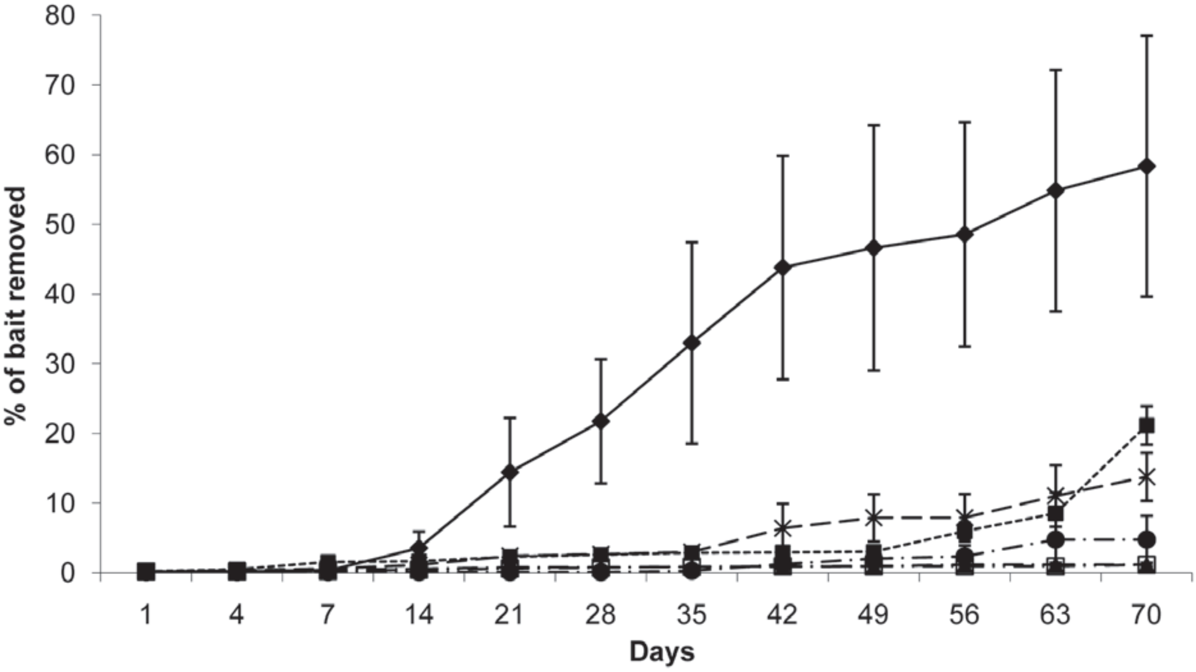

Figure 2. Mean (± SE) proportion (%) of six bait types removed by invertebrates at four sites: Collie, Kalgoorlie, Manjimup and Narrogin. Diamond = DMB; filled square = standard Pro-bait; triangle = Pro-bait with added Coopex; cross = hard Pro-bait; open square = hard Pro-bait with added Coopex; circle = Foxoff bait.

Table 1

Preferences shown by foxes for six flavoured versus control lures at Karara station (KS) and Thundelarra station (TS). Fox = the lure type on the cyanide capsule that killed a fox; Single = the lure type removed from one of a pair of cyanide capsules (if both lures were removed no preference could be assigned); n. s. = not significant.

			Beef	Chicken	Ethyl caproate	Hexylamine	Honey	MSG
KS	Fox	Flavour	1	7	2	0	2	6
		Control	1	1	6	5	0	7
	Single	Flavour	5	12	6	5	3	10
		Control	12	2	17	24	5	9
	Total	Flavour	6/19	19/22	8/31	5/34	5/10	16/32
		Control	13/19	3/22	23/31	29/34	5/10	16/32
TS	Fox	Flavour	1	2	0	0	2	1
		Control	3	2	5	17	2	2
	Single	Flavour	0	3	4	2	2	0
		Control	0	0	6	27	4	1
	Total	Flavour	1/4	5/7	4/15	2/46	4/10	1/4
		Control	3/4	2/7	11/15	44/46	6/10	3/4
Total		Flavour	7/23	24/29	12/46	7/80	9/20	17/36
		Control	16/23	5/29	34/46	73/80	11/20	19/36
χ^2			1.83	6.97	5.58	32.81	0.1	0.06
p			n. s.	$p<0.01$	$p<0.05$	$p<0.001$	n. s.	n. s.

Phase 4: A field trial to compare the uptake of DMB and reformulated Pro-bait by foxes

When the background IPA results obtained from the four foxes sampled at CDR were combined with those obtained during the 1999 trial, a mean background iodine level for the eight foxes was 23.7 ug L^{-1} (SD = 24.4). Therefore, any fox with a blood iodine level above 72.5 ug L^{-1} (i.e. mean + 2 SD) was concluded to have ingested an IPA-labelled bait. This value is slightly lower than that used by Fleming (1997; 168–1717 ug L^{-1}).

Fifty fox carcasses were collected from Lochada station and 54 from CDR. A blood sample was not obtained from two foxes recovered from Lochada station and one fox from CDR because their blood had coagulated overnight. The teeth of one fox from CDR were either missing or rotten and so no sample could be collected.

At CDR, 46 of the 53 foxes ingested a DMB and 48 foxes ingested a Pro-bait (X^2 = 0.38). At Lochada, 44 of the 50 foxes recovered ingested a DMB and 40 of 48 foxes ingested a Pro-bait (X^2 = 0.44). There were no significant differences between uptake of the different baits at either site or when the data from both sites were pooled. Foxes ingested 87% of both bait types.

DISCUSSION

The uptake of Pro-baits was significantly lower than that of DMBs in Phase 1 of the experiment and this was attributed to a possible difference in field longevity between the two bait types. Pro-baits, which are made of minced meat (Armstrong 2004), were suggested to be more prone to invertebrate damage or weathering than DMBs, which are made from a single piece of kangaroo meat (Thomson & Algar 2000). During Phase 1, Pro-baits at Wagga Wagga station had the lower rate of uptake and this was postulated to have been caused by the higher rainfall at this site during the experiment. However, the results of the bait longevity trial in Phase 2 showed that Pro-baits were able to withstand invertebrate damage significantly better than DMBs, irrespective of the amount of rainfall at four study sites.

DMBs suffered significantly more invertebrate damage than any of the other bait types tested and were very susceptible to damage by *Demestes* beetle larvae and meat ants (*Iridomyrmex* spp.). Similar invertebrate damage to baits, especially that caused by meat ants, maggots and beetles, has been observed in other bait uptake trials (McIlroy et al. 1988; Fleming & Parker 1991; Saunders et al. 2000). McIlroy et al. (1988) stated that the amount of damage sustained by baits was related to the geographical and seasonal distribution of invertebrates, their abundance, the weather conditions, and the shape and condition of the baits. They also observed that invertebrate damage was responsible for more bait deterioration than rainfall and this is consistent with observations made during the current study. However, in contrast, Twigg et al. (2000) found very little evidence of insect damage to DMBs tested in central Australia, but this may have resulted because their trial was undertaken in an arid site and their baits became desiccated and developed an especially dry, tough outer skin that may have prevented invertebrate damage.

In comparison with DMBs, standard Pro-baits sustained very little invertebrate damage and this was significantly reduced through the addition of an invertebrate deterrent, though increasing the hardness of Pro-baits did not affect their durability. These results reveal that the observed difference in uptake between Pro-baits and DMBs by foxes in Phase 1 was not explained by a difference in bait longevity.

The lesser uptake of Pro-baits was therefore concluded to be due to lower acceptability of the manufactured bait. In an attempt to increase the acceptability of Pro-baits, a flavour that was attractive to foxes was sought for inclusion in the bait's recipe. Foxes showed a significant preference for chicken flavour but were indifferent to beef or honey flavours and to monosodium glutamate. These results are in contrast with observations by Saunders & Harris (2000) who found that captive foxes preferred beef and honey flavours. Their result may have occurred because they used a bran-based control bait that contained no meat whereas in this study all lures contained meat and consequently any preference for a beef flavour would have been diminished. Saunders & Harris (2000) also observed that ethyl caproate and hexylamine were not attractive to captive foxes and this is consistent with the avoidance of these chemicals by foxes in the current study.

The uptake of Pro-baits that had been reformulated to include the chicken flavour enhancer was compared with that of DMBs in a second trial (Phase 4). There was no difference in the ingestion rate of the two bait types and both had an uptake of 87%. This level of uptake exceeds that of some other bait types developed for fox control (e.g. 23% D-K9 bait uptake [Fleming et al. 1992] and fresh meat baits 69.5% [Thompson & Fleming 1994]) but is similar to the uptake of Foxoff baits (90%; Applied Biotechnologies 1994) and to DMBs tested in other field trials (mean 79.5%; Thomson & Algar [2000]; >95%, Thomson et al. [2000]). The 87% uptake of Pro-baits occurred irrespective of any potential for caching (Kay et al. 1999; Thomson & Kok 2002; Gentle et al. 2007) that may have resulted if its palatability had been low (van Polanen Petel et al. 2001). This level of Pro-bait uptake is sufficient to achieve the 75–80% fox reduction necessary for the prevention of rabies (Trewhella et al. 1991) and, because it equals that of the DMB (Thomson et al. 2000), it is sufficient to promote fauna recovery.

Before the operational use of re-formulated Pro-baits could be approved, CALM needed to ensure there was no increased non-target risk of using Pro-baits rather than DMBs. Martin et al. (2003) had investigated the rate of ingestion of Pro-baits and DMBs by a range of endemic species in captivity and found brush-tailed phascogales (*Phascogale tapoatafa*) and chuditch (*Dasyurus geoffroii*) to potentially be at risk from the ingestion of Pro-baits. All other species investigated consumed too little Pro-bait material (or DMBs) to ingest a lethal dose of 1080. The response of phascogale and chuditch populations to an operational fox baiting programme was examined and the results of these two studies demonstrated that baiting with Pro-baits did not detrimentally impact either species (Morris et al. 2005; Marlow et al. 2015).

Once Pro-baits had been shown to be as efficacious as DMBs without increased non-target risk they could be registered for operational use. Initially an application was made to register Pro-baits with the invertebrate repellent 'Coopex®' included in their formulation. However, due to potential synergistic actions of this chemical and 1080, which precluded registration without exhaustive testing, it was decided to exclude this agent. Pro-baits were registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA) for use in Western Australia in 2002. In future this registration of Pro-baits may possibly be expanded so that they can be used to deliver substances other than 1080, which may include cabergoline for the reproductive control of foxes (Marks et al. 2001), a potential immunocontraceptive vaccine (Bradley et al. 1996), or alternative toxins such as PAPP (Fleming et al. 2006). In late 2005, Parks and Wildlife officially endorsed the use of Pro-baits for use in *Western Shield* fox control operations. Subsequently, the Harvey bait manufacturing facility was expanded to produce sufficient baits for the entire *Western Shield* fauna recovery programme and the operational use of Pro-baits commenced.

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Assessing the impact of 1080 Pro-baits on wild brush-tailed phascogales (*Phascogale tapoatafa*) during an operational fox baiting campaign

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ABSTRACT

Brush-tailed phascogales were potentially at risk from poisoning from a newly developed fox bait, Pro-bait. Before Pro-baits were used operationally their impact upon a population of phascogales was investigated. Seven radio-collared brush-tailed phascogales (*Phascogale tapoatafa,* undescribed subspecies) were monitored for nine weeks during and after a fox-baiting program using toxic Pro-baits. Each Pro-bait contained 3 mg 1080 (sodium fluoroacetate) and the biomarker dye, Rhodamine B. Baits were aerially delivered to the Catterick Forest Block site on 2 April 2005 at the rate of 5 baits km^{-2}. Additional baits were hand laid near known phascogale locations on 23–24 May 2005. No radio-collared phascogales died, though one collar failed. All other collars were removed on 8 June 2005. No evidence of the biomarker that would indicate bait ingestion was observed in 104 whisker samples taken from the recaptured phascogales. Four scats were collected during trapping in April–May 2005 and another four scats were collected in June 2005. One scat collected on 29 April 2005 had a pink hue suggesting the presence of Rhodamine B, but it did not fluoresce under ultraviolet light. Its colour may have resulted from the ingestion of some other pink-coloured foodstuff. It was concluded that phascogales were unlikely to ingest Pro-baits during operational fox baiting programs and mortality through poisoning would not occur on a scale likely to affect the overall population.

Keywords: bait development, fox, introduced predator control, phascogale, 1080

INTRODUCTION

The *Western Shield* fauna recovery program aims to reduce fox (*Vulpes vulpes*) predation on vulnerable endemic fauna and to maximise the sustainable recovery of wildlife populations (Possingham et al. 2004). This program was launched by the Department of Parks and Wildlife (Parks and Wildlife, then the Department of Conservation and Land Management [CALM]) in 1996 and it relies on the repeated delivery of meat baits containing the poison 1080 (sodium fluoroacetate). 1080 is used in this fox control program because of its high toxicity to canids (McIlroy 1981; McIlroy et al. 1986; McIlroy & King 1990). Many endemic species in south-western Australia have developed a tolerance to fluoroacetate through their co-evolution with fluoroacetate-bearing vegetation (King et al. 1978, 1981; Calver et al. 1989; Twigg & King 1991), and this ensures that 1080 baiting campaigns are particularly target-specific in Western Australia.

Initially the *Western Shield* program obtained its fox baits, dried meat baits (DMBs), from the Department of Agriculture and Food Western Australia. These baits were delivered to approximately 3.4 M ha at least four times each year (Armstrong 2004). The program was so successful that the woylie (*Bettongia penicillata*), the tammar wallaby (*Macropus eugenii*) and the quenda (*Isoodon obesulus*) were removed from the state's threatened species list in 1996 (Mawson 2004). In 1998, CALM decided to develop a sausage-style bait, Pro-bait, to reduce the cost of the *Western Shield* program (Armstrong 2004). The cost of Pro-bait manufacture is lower because they are made from minced kangaroo meat that is cheaper and more readily available than the chunks of meat required for the production of DMBs. Pro-bait production is based on a salami manufacturing process and the advantages of this are automation, large economically effective production runs, minimal wastage and improved shelf life of baits. The uniform shape and size of this bait type also improves packaging efficiency and reduces transport and storage costs (Armstrong 2004).

Before Pro-baits could be used operationally they had to be shown to be as effective at controlling foxes as DMBs and to pose no more of a risk to non-target wildlife. Various uptake trials, longevity assessments and amendments to the recipe for Pro-baits were undertaken to ensure they were as palatable to foxes as DMBs (Marlow et al. 2015a).

The potential risk of Pro-baits and FOXOFF® baits to non-target species had been investigated in captive trials (Martin et al. 2002). In those trials the ingestion of the two bait types by 15 potentially susceptible non-target species was compared with that of DMBs. The species selected for testing were chosen based upon their diet, their sensitivity to 1080, and their size relative to the probable 1080 loading of baits they may encounter (Martin et al. 2002). The results of these trials indicated that the brush-tailed phascogale (*Phascogale tapoatafa*, undescribed subspecies) was potentially at risk from operational fox-baiting campaigns using Pro-baits. Chuditch (*Dasyurus geoffroii*) were also potentially at risk from Pro-baits but were at more risk from DMBs (Martin et al. 2002). The potential risk to brush-tailed phascogales from the operational use of Pro-baits was of particular concern to the department because there had been anecdotal reports of their abundances decreasing in areas where fox baiting with DMBs occurred and they had been found to be more susceptible to 1080 poisoning than previously recognised (Twigg et al. 2004).

The actual risk of Pro-baits to brush-tailed phascogales was investigated in a trial in which toxic 3 mg 1080 Pro-baits were delivered at the standard baiting rate (5 baits km^{-2}) to a population of brush-tailed phascogales, in which seven animals were radio-collared. The Pro-baits also contained a biomarker dye, Rhodamine B, which would label the whiskers and scats of individuals that ingested it (Fisher 1999). The results of these trials were used to estimate the proportion of brush-tailed phascogales that would consume Pro-baits in the field.

METHODS

Bait characteristics

Pro-baits are a sausage bait that contain 70% minced kangaroo meat, 20% animal fat (pork or chicken), canine 'digest' (a commercial flavour enhancer for dog food) and other flavour enhancers (Armstrong 2004; Marlow et al. 2015a). A salami-style binder is added to this mixture to promote hardening of the final product. This reduces the risk of smaller non-target species being able to bite into the bait (Martin et al. 2002). The toxin 1080 is added as a solution and is automatically injected into each bait as it is formed in the sausage-making machine. Each bait weighs approximately 80–85 g at manufacture and is then heated to between 30–40 °C to promote uniform shrinkage during the drying process. The baits are then dried to approximately 40 g before delivery to the field (Armstrong 2004).

Pro-baits were labelled with the biomarker Rhodamine B. This biomarker produces persistent systemic markings in the hairs and faeces of mammals that ingest the baits and these are detectable under ultraviolet light (Fisher et al. 1999). Pro-baits were labelled with Rhodamine B by inserting 0.5 ml aqueous solution (40 mg ml^{-1}) into a 2 mm diameter hole that had been drilled into the side of each bait with an electric drill. This volume of Rhodamine B was sufficient to deliver the recommended dose for mammals of 15–35 mg kg^{-1} (Spurr 2002). The addition of the biomarker was intended to simulate the addition of 1080 and so was injected into one site.

The study site

The experimental site was at Catterick Forest Block, a 6550 ha area approximately 10 km east of Balingup and 230 km south of Perth, Western Australia (Fig. 1). This forest block is in the southern jarrah forest IBRA region, near the southern edge of the Darling Plateau, and exhibits the Darling Uplands subtype of the Darling Plateau Landscape Character Type. It has winter-dominant rainfall of 800–900 mm per annum. It is in the Darling Botanical District and is characterized by open forest of *Corymbia calophylla – Eucalyptus marginata* with *E. wandoo* and *E. patens* on slopes, woodlands of *E. rudis* and *Melaleuca rhaphiophylla* on lower slopes, and *E. rudis* and *Banksia littoralis* on valley floors. It has moderately fertile grey-brown earths and yellow or red duplex soils with a gravelly sand loam topsoil over clay (Havel & Mattiske 2000).

Baiting

Catterick Forest Block was aerially baited every three months with DMBs at the standard baiting regime (5 baits km^{-2}; Armstrong 2004). Regular baiting at this site commenced in 1998. Pro-baits containing 3 mg 1080 and Rhodamine B were aerially delivered to Catterick Forest Block during the scheduled *Western Shield* baiting event on 2 April 2005. The location of all Pro-baits delivered was recorded using a GPS (model GPS76; Garmin Corporation, Kansas USA). To ensure Pro-baits were available to brush-tailed phascogales, additional Pro-baits were hand laid at Catterick Forest Block on 23–24 May 2005. Five Pro-baits were positioned near the diurnal resting site of each of the six brush-tailed phascogales that were being monitored. One bait was placed at the base of the inhabited tree and another four baits were placed 200 m from this central point; one at each of the four major compass points.

Trapping and monitoring

The primary method of determining if toxic Pro-baits were lethal to brush-tailed phascogales was through monitoring the survival of radio-collared individuals. Phascogales were initially trapped and radio-collared between 15–20 March 2005. One hundred Sheffield cage traps (Sheffield Wire Products, Welshpool, WA) and 17 small Elliott traps

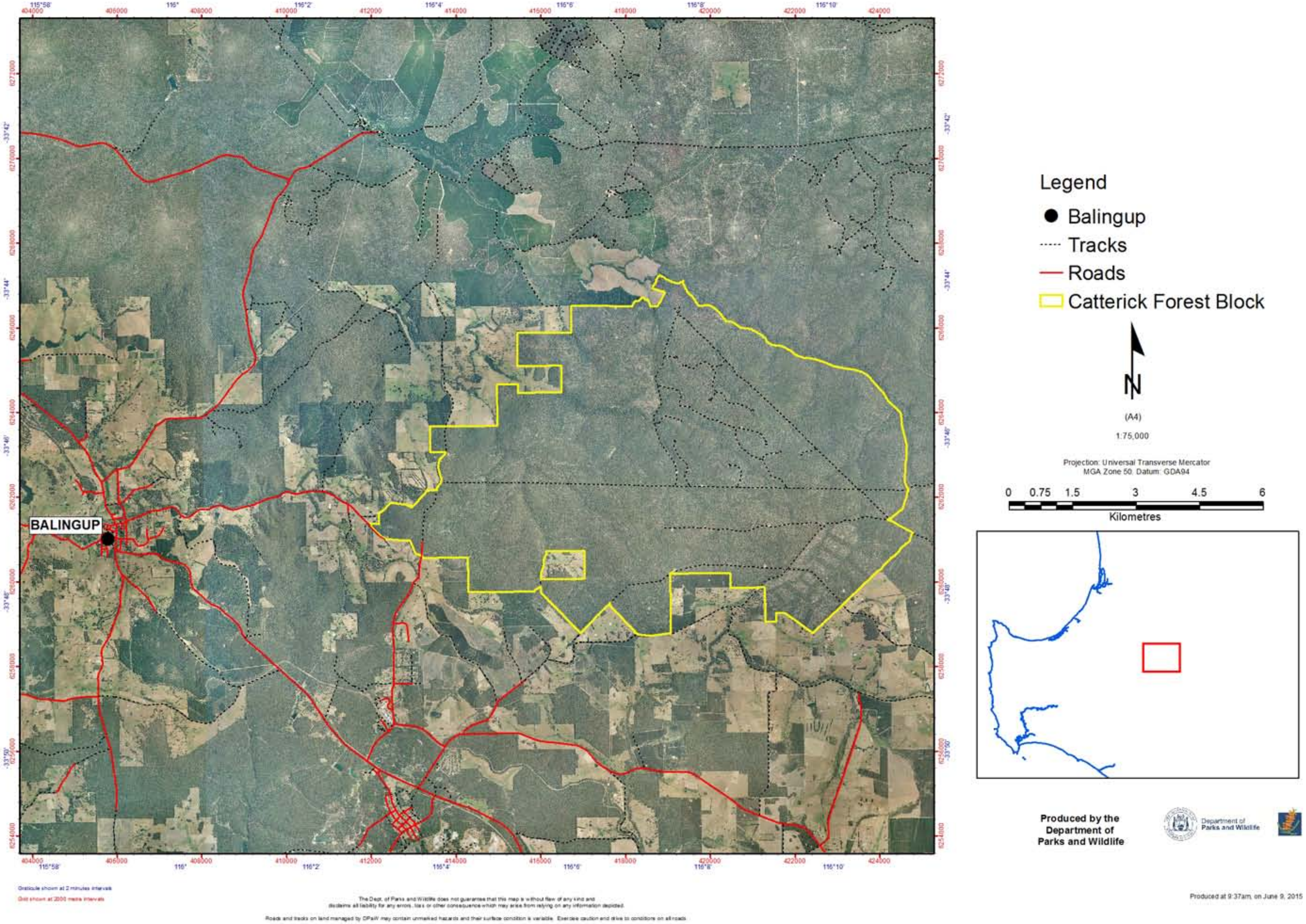

Figure 1. Map of the study site at Catterick Forest Block.

Table 1

Trapping effort for brush-tailed phascogales during 2005.

Date	No. trap nights, cage traps	No. trap nights, Elliott traps	No. individuals captured
15–20 March	500	85	6 new
26–28 April 2–4 May	240	48	6 (1 new, 5 recaptures)
8 June	72	0	6 (all recaptures)

(Elliott Scientific Equipment, Upwey, Victoria), baited with peanut butter, oats and sardines, were set at 200 m intervals along vehicle tracks. Trapped phascogales were fitted with Biotrack P1P2 (Biotrack, UK) radio–collars. Radio-collared individuals were tracked to their diurnal refuge sites at least once per week but more often where possible (Table 2). The survival of these phascogales was monitored during the operational delivery of Pro-baits and after the hand-placement of baits near to their known resting sites. It was anticipated that if phascogales ingested a lethal dose of 1080 their death would occur within approximately four hours (Potter et al. 2006).

Trapping was repeated in April–May and June 2005 but only cage traps were used and these were strategically positioned to recapture collared individuals. All brush-tailed phascogales were weighed at each capture using a 500 g capacity Pesola scale (Prospectors Earth Sciences, Seven Hills, Australia). A qualitative assessment of the condition of phascogales was made at the initial and final captures. A sample of 6–10 whiskers was plucked from each captured individual (as recommended by Spurr 2002) in each of the March–April and June trapping sessions (Table 1). Any scats deposited in traps were collected. Whiskers and scats were later examined for the presence of the biomarker Rhodamine B. Whiskers were examined using a fluorescence microscope as described by Fisher et al. (1999). In small mammals, Rhodamine B is detectable in whiskers from 12 hours to 17 weeks after bait ingestion (Jacob et al. 2002), and in scats the ingestion of the dye can be detected for up to two days after bait consumption (Jacob et al. 2002).

RESULTS

Trapping and monitoring

During the 15–20 March 2005 trapping session, six brush-tailed phascogales (3 males, 3 females) were captured and radio-collared at Catterick Forest Block (Table 1). Trap success was higher with cage traps than Elliott traps (five captures versus one) and so the use of Elliott traps was phased out during the experiment. Radio-collared brush-tailed phascogales were monitored regularly (Table 2). The signal from one male phascogale (M#15) was lost on 5 April 2005 but this individual was later re-trapped and re-collared on 27 April 2005. The signal from another male (M#14) was lost on 27 April 2005 and was not

Table 2

Dates of collaring (C), re-collaring (RC), monitoring (Y = signal present, N = no signal present) and collar removal (CR) of brush-tailed phascogales in relation to aerial and hand delivery of Pro-baits at Catterick Forest Block in 2005.

Date	F#12	M#13	M#14	M#15	F#16	F#17	M#18
15 Mar	C						
16 Mar	Y						
17 Mar	Y	C	C				
18 Mar			Y				
19 Mar	Y	Y	Y	C	C		
20 Mar		Y		Y	Y	C	
22 Mar	Y	Y	Y	Y	Y	Y	
29 Mar	Y	Y	Y	Y	Y	Y	
2 Apr	Aerial Pro-bait delivery						
5 Apr	Y	Y	Y	N	Y	Y	
11 Apr	Y	Y	Y	N	Y	Y	
18 Apr	Y	Y	Y	N	Y	Y	
26 Apr	Y	Y	Y	N	Y	Y	
27 Apr	Y	Y	N	RC	Y	Y	
28 Apr	Y	N	N	Y	Y	Y	
29 Apr					RC		C
2 May	Y	N	N			N	
3 May	Y	RC	N	N	Y	Y	Y
4 May	RC			N		RC	
5 May	Y	Y	N	Y	Y	Y	Y
17 May	Y	N		Y	Y	Y	Y
23 May	Y	Y		Y	Y	Y	Y
23–24 May	Hand Pro-bait delivery						
26 May	Y	Y		N	Y	Y	Y
3 Jun	Y	Y		Y	Y	Y	Y
8 Jun	C	CR	N	CR	CR	CR	CR

Table 3

Duration of monitoring of radio-collared brush-tailed phascogales in Catterick Forest Block in 2005 before and after aerial and hand delivery of Pro-baits, respectively.

ID	Initial weight (g)	Final weight (g)	No. days monitored pre-aerial Pro-bait delivery	No. days monitored post-aerial Pro-bait delivery	No. days monitored pre-hand Pro-bait delivery	No. days monitored post-hand Pro-bait delivery
F#12	130	120	18	67	69	16
M#13	150	149	16	67	67	16
M#14	150	n/a	16	24	n/a	n/a
M#15	155	140	14	67	65	16
F#16	110	112	14	67	65	16
F#17	130	118	13	67	64	16
M#18	155	162	0	40	24	16

relocated. A new male (M#18) was trapped and collared on 29 April 2005. All six brush-tailed phascogales with functional collars were re-trapped on 8 June 2005 and their collars removed. All animals were assessed to be in good condition at each capture and no females had any pouch young.

All phascogales survived and were monitored for an average 57 days (± 17 SD; Table 3) after the aerial delivery of Pro-baits. They also survived for 16 days after hand delivery of Pro-baits (except M#14 whose signal was lost).

Biomarker detection

A total of 104 whisker samples was collected from seven individual phascogales. Of these, 56 were collected at least 24 days after the aerial baiting with toxic Pro-baits (mean 57 days ± 17 SD; Table 3) and 48 were collected 16 days after the strategic placement of baits around diurnal resting sites (i.e. 67 days after initial exposure to toxic baits; Table 3). None contained any evidence of the biomarker.

Four scats were collected during the April–May 2005 trapping session (i.e. at least 24 days after aerial Pro-bait delivery) and one of these (from F#16 on 29 April 2005; 27 days after aerial Pro-bait delivery) had a pink hue. This colouration may have been due to the presence of the Rhodamine B biomarker but this was not conclusive because it did not fluoresce under ultraviolet light. It may have resulted from the individual ingesting a pink-coloured invertebrate or other foodstuff. A further four scats were collected during the June 2005 trapping session, which was undertaken 16 days after the strategic placement of additional Pro-baits near the known locations of radio-collared brush-tailed phascogales, but none of these scats revealed the biomarker.

DISCUSSION

There was no evidence from whisker marking that brush-tailed phascogales removed or ingested 3 mg 1080 Pro-baits delivered at the standard fox-baiting rate of 5 baits km^{-2}. Although one female may have ingested a Pro-bait, as evidenced by pink colouration in a scat, no mortality of collared brush-tailed phascogales occurred. When additional Pro-baits were positioned at known locations of brush-tailed phascogales no further evidence of bait ingestion was detected and all individuals maintained their weight and general body condition.

The concerns raised by Martin et al. (2002) that brush-tailed phascogales may be at risk from toxic Pro-baits during operational fox-baiting programs were not realised. Martin et al. (2002) acknowledged that they used the worst-case scenario, and therefore the conservative approach which follows the 'precautionary principal' (Calver et al. 1999), in their assessments of risk. They defended their stance by stating that it is well recognised that food consumption by free-ranging animals can be more than two-fold greater than that of captive-held animals (McIlroy 1981; Nagy et al. 1988; Calver et al. 1990). This may lead to an underestimate of the amount of 1080 potentially ingested by non-target species based on their consumption of non-toxic baits in the laboratory (McIlroy 1981). Also, once encountered, a predator bait is likely to provide an easy meal for carnivorous non-target species with a reduced need to hunt prey. One reason brush-tailed phascogales may not have ingested Pro-baits may be that they are able to detect 1080 in a similar manner to that described for dunnarts (*Sminthopsis crassicaudata*; Sinclair & Bird 1984). Also, if phascogales vomit after the ingestion of even a small amount of meat containing 1080, as dunnarts do, then they are unlikely to be at risk from operational baiting campaigns (Sinclair & Bird 1984).

Martin et al. (2002) recognised that other species they identified as potentially being at risk from baits were not detrimentally affected when actually exposed to toxic fox baits during a baiting program. They describe how chuditch and northern quolls (*D. hallucatus*) were considered to be theoretically at risk from baiting operations by Calver et al. (1989), Soderquist & Serena (1993), and in their own study (2002), but that those concerns were not realised when the survival of these species was monitored during routine control operations by King (1989) and Morris et al. (1995).

Brush-tailed phascogales have been observed to ingest fox baits in other studies. Fairbridge et al. (2003) reported that 15% of the 40 brush-tailed phascogales they monitored at the Puckapunyal Military Area in central Victoria ingested buried non-toxic 30 g FOXOFF® baits.

The factors that may have affected those bait ingestion rates included the timing of bait lay, the hardness, composition and size of baits, and the density of baits deployed. The timing of bait lay was unlikely to have been responsible for the observed differences in bait uptake between Victoria and the current study. Although Fairbridge et al. (2003) undertook their trial during summer and autumn when juveniles were becoming independent and adult females may have been nutritionally stressed, the current study was also undertaken in autumn, and although no juveniles were present, adults may similarly have been nutritionally stressed.

The hardness and size of the bait types used in the two experiments may account for the observed differences in uptake. FOXOFF® baits are soft and moist (Martin et al. 2002) and are smaller than Pro-baits (30 g versus 40–45 g). Softer and smaller baits are more easily handled and consumed by small non-target mammals that lack the dentition to eat substantial amounts of large, harder baits (Calver et al. 1989; Martin et al. 2002). The hardness of the bait matrix has been observed to influence bait consumption by non-target dasyurid species (Soderquist & Serena 1993; Martin et al. 2002; Fairbridge et al. 2003). FOXOFF® baits are readily accepted by eastern (*D. viverrinus*) and spotted-tailed quolls (*D. maculatus*) from eastern Australia (Belcher 1998) and were also consumed much more readily than Pro-baits or DMBs by spotted-tailed quolls, eastern quolls and northern quolls (*D. hallucatus*) in captivity (Martin et al. 2002). The observed differences in uptake of FOXOFF® and Pro-baits by brush-tailed phascogales may be due to Pro-baits being larger and specifically formulated to include a binder to render baits harder so as to reduce non-target ingestion (Marlow et al. 2015a). The size of baits will also influence the hazard to non-target species (Martin et al. 2002) because the toxin in smaller baits will be relatively more concentrated if they contain the same amount of 1080 as larger baits. Ideally larger baits should be used to reduce risks to non-target species, though this attribute needs to be balanced against the possibility that larger baits are potentially more likely to be cached than smaller baits.

The density of baits available to brush-tailed phascogales may also have influenced the difference in observed bait ingestion rates between Victoria and Western Australia. Fairbridge et al. (2003) wanted to test whether brush-tailed phascogales had the propensity to eat fox baits deployed in buried bait stations. They used parallel transects positioned 100 m apart with bait stations located at 50 m intervals. Their extrapolated bait delivery rate would therefore have been approximately 200 baits km^{-2}, which is about 40 times greater than the standard baiting rate of 5 baits km^{-2} used in Western Australia (Armstrong 2004). In Western Australia there would be one bait delivered every 20 ha but the number of baits actually available to phascogales may be much lower due to a very high ingestion rate of baits by brush-tailed possums, birds and other non-target species (Marlow et al. 2015b). Given the average home range areas used by female and male phascogales in these areas are 20 ha and 25.9 ha respectively (Rhind 1998), it is unlikely that many baits will be detected. The foraging behaviour of brush-tailed phascogales may also reduce bait consumption because this arboreal species was observed to spend little time foraging at ground level, at least in south-western Australia (Scarff et al. 1998). Even when additional baits were laid in the current study the probability of brush-tailed phascogales encountering a bait would be low.

If the use of Pro-baits was to be expanded to eastern Australia, field trials would need to be undertaken to ensure that non-target species that have not had evolutionary exposure to fluoroacetate-bearing vegetation would not be at risk (Mead et al. 1985; Twigg & King 1991). Some mammals from eastern Australia would be placed in a moderate to high theoretical risk category if they ingested 3 mg Pro-baits due to their higher level of sensitivity to 1080 (Martin et al. 2002). The sensitivity to 1080 of brush-tailed phascogales from eastern Australia has not been assessed but they are likely to be more sensitive than the Western Australian conspecific (Twigg & King 1991). Therefore populations of this species in the eastern states should be monitored for potential non-target impacts if baiting with Pro-baits was ever to be introduced (Martin et al. 2002).

Although brush-tailed phascogales have been shown not to be at risk from operational fox-baiting campaigns in Western Australia, there are still some factors that need to be considered when predator baiting campaigns are undertaken (Martin et al. 2002). If the food supply of phascogales is known to be reduced, the potential protection this species may be afforded by predator baiting needs to be weighed against a greater risk to them from Pro-baits (and other predator baits) when no alternative food is available (Martin et al. 2002). Similarly, if juveniles are present, their inclination to consume baits because they are less experienced hunters (Soderquist & Serena 1993) needs to be balanced against the protection they would acquire from predator control. Also, if possible, baiting should not be undertaken immediately preceding and during the breeding season of dasyurids that undergo post-mating male die-off. Although Morris et al. (2005) found that adult and juvenile chuditch were unaffected by toxic Pro-baits in the field, it would be prudent to undertake adequate monitoring of chuditch and phascogale populations in areas where fox baiting programs are routinely undertaken to detect non-target mortality if it occurs.

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