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Review

Research priorities for the northern quoll (*Dasyurus hallucatus*) in the Pilbara region of Western Australia

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Abstract. The Pilbara population of the northern quoll (*Dasyurus hallucatus*) has been seldom studied, and the impacts of threats such as altered fire regimes, total grazing pressure, predation and mining and infrastructure development are not well understood. While the Pilbara was once thought likely to provide refuge for northern quolls from the poisonous cane toad (*Rhinella marina*), recent modelling suggests that cane toads will invade the region. The environmental approvals process for mining development in the Pilbara has generated considerable offset funds that are to be directed towards research on the northern quoll. In an effort to identify future research priorities for this species in the Pilbara through a collaborative process, the Western Australian Department of Parks and Wildlife hosted a workshop attended by scientists, environmental consultants, mining proponents and state and federal regulators. Participants at the workshop identified five key areas for future research effort: (1) develop appropriate and standardised survey and monitoring methods; (2) define areas of critical habitat and better understand how disturbance affects habitat quality; (3) improve our understanding of population dynamics; (4) better understand the key threats to the northern quoll and the interactions between these threats in the Pilbara; and (5) determine whether the northern quoll will colonise restored areas or artificial habitat. We provide the expected timelines and current allocation of resources to these research priorities over the next 10 years. We reflect on the lessons learnt from the workshop process and consider ways to improve the outcomes of such collaborative exercises.

Additional keywords: cane toads, den sites, habitat quality, monitoring, population structure, predators.

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Introduction

The northern quoll (*Dasyurus hallucatus*) is the largest predatory dasyurid marsupial remaining in northern Australia. It was formerly distributed from the Pilbara and Kimberley across the Top End to southern Queensland, but has now contracted to several disjunct populations (Braithwaite and Griffiths 1994). Several interacting ecological factors, primarily predation by cats (*Felis catus*) and foxes (*Vulpes vulpes*) and changed fire regimes, are currently causing rapid and severe declines in the small- and medium-sized mammal fauna of northern Australia (Woinarski *et al*. 2014, 2015). In addition, an alarming decrease or complete collapse in some of the once locally abundant populations of the northern quoll in Queensland and the Northern Territory has occurred as a direct result of the invasion of the cane toad (*Rhinella marina*) (Burnett 1997; Oakwood and Foster 2008; Woinarski *et al*. 2010). While the Pilbara region and its offshore islands were formerly thought likely to remain free of cane toads, and therefore provide a 'stronghold' for the northern quoll, it is now predicted that cane toads will invade the Pilbara, and may even be able to reach its offshore islands (Kearney *et al*. 2008; Tingley *et al*. 2013). Owing to these factors, the northern quoll is listed as Endangered under both the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (*EPBC Act 1999*) and the Western Australian *Wildlife Conservation Act 1950*.

While the ecology of the northern quoll has been studied in the Northern Territory (Begg 1981; Braithwaite and Griffiths 1994; Oakwood 1997, 2000, 2002), and to a lesser extent in the Kimberley (Schmitt *et al*. 1989; How *et al*. 2009; Cook 2010), few studies have been undertaken on the northern quoll in the Pilbara. A 10-year monitoring program that includes the collection of demographic and habitat data is being undertaken by the Western Australia Department of Parks and Wildlife (hereafter Parks and Wildlife), and commenced in 2014. The extent of occurrence of the northern quoll in the Pilbara and

Kimberley is estimated to be ~12 000 000 ha, but the area of occupancy and the number of mature individuals within the two regions are not known (Parks and Wildlife, unpubl. data). Approximately 2500 records for the northern quoll (many of which are highly clustered) are held in the NatureMap database (http://naturemap.dpaw.wa.gov.au); these include records from the Western Australian Museum and Parks and Wildlife, and fauna returns from surveys undertaken by private groups (mostly environmental consultants). These location records indicate that quolls are more prevalent in complex, rocky areas in the north, central and west Pilbara, and are less likely to occur through the south and east areas of the Hamersley Ranges and Fortescue Marsh (Fig. 1). The Pilbara population is genetically distinct from the Kimberley and Northern Territory populations (Woolley *et al*. 2015) and is the least diverse, with ~77% heterozygosity (10.3 alleles) compared with 84% heterozygosity (11.1 alleles) in the Kimberley mainland population (How *et al*. 2009; Spencer *et al*. 2013).

Habitat change due to altered fire regimes, weed invasion and grazing, predation by cats, foxes and dingoes/wild dogs, the future invasion of cane toads, and the interactive effects between these, as well as habitat fragmentation and loss by mining and infrastructure development, have been identified as key threats for the northern quoll in the region (Woinarski *et al*. 2014). While the potential invasion of the cane toad is undoubtedly the most significant future threat to the northern quoll in the Pilbara, there is little knowledge of what has been the relative impact, or the interactive effects, of each of the other key threats on the northern quoll in the region, or how these will affect northern quoll populations into the future.

The areas of highest habitat quality for the northern quoll are considered to be rugged, rocky areas, often in close association with permanent water (Begg 1981; Schmitt *et al*. 1989; Braithwaite and Griffiths 1994; Oakwood 1997; Pollock 1999). These rocky landforms provide a diversity of environments, denning opportunities, protection from weather and diurnal predators and immediate refuge from fire (Braithwaite and Griffiths 1994; Oakwood 2000; Cook 2010). In the Pilbara, the ridges and mesas of channel-iron deposits and banded iron formation ranges are often the primary focus of iron-ore extraction (Ramanaidou and Morris 2010), while exposed granite outcrops are quarried for road and rail beds. The northern quoll is therefore a key consideration in most mining project assessments under the *EPBC Act 1999* in the Pilbara, as well as two strategic environmental assessments examining the cumulative impacts of mining in the region (BHP Billiton Iron

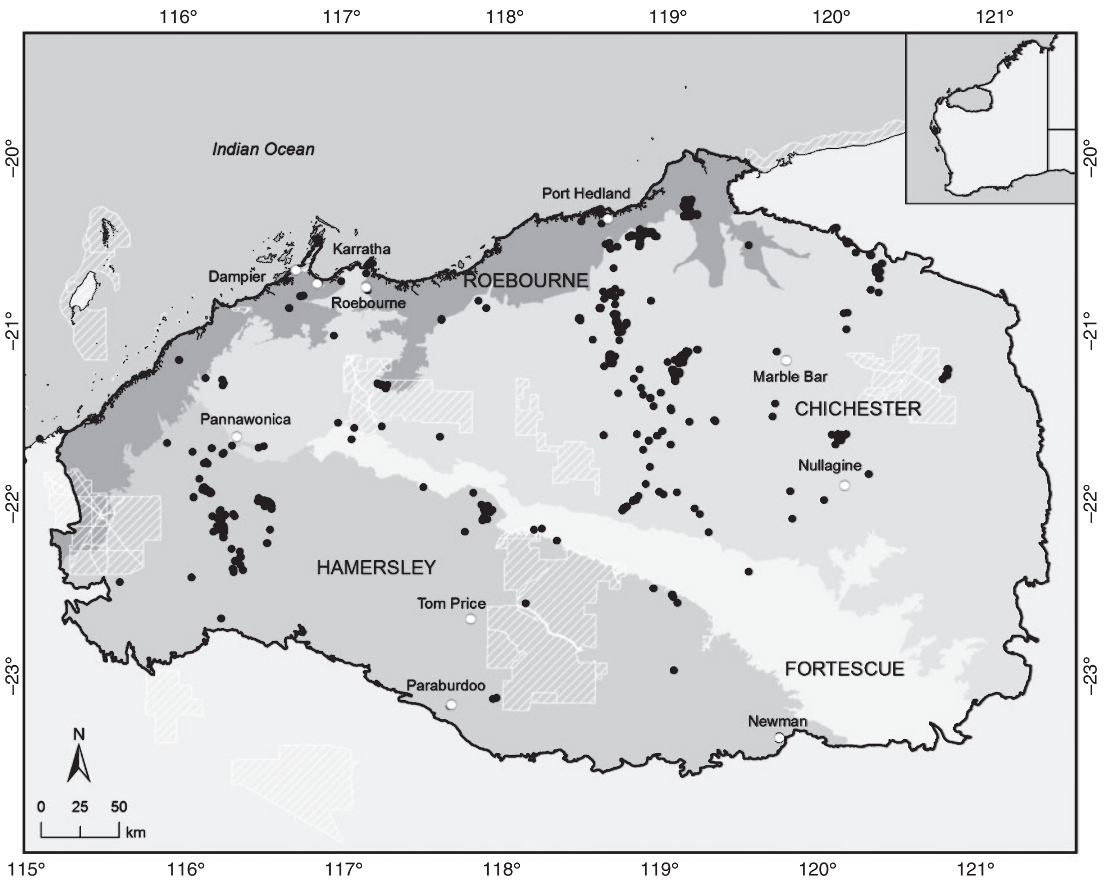

Fig. 1. Records (black dots) of the northern quoll in the Pilbara obtained from the Department of Parks and Wildlife NatureMap database (http://naturemap.dpaw.wa.gov.au). The shaded areas indicate the IBRA subregions, and the hatched areas the conservation estate within the region. Much of the recent survey effort has occurred in areas with mining activity or mining-related infrastructure, e.g. the rail corridors running south of Port Hedland.

Ore, http://www.environment.gov.au/node/18597; Hamersley Iron Pty Ltd (Rio Tinto), http://www.environment.gov.au/node/18608).

Biodiversity offsets are increasingly used as a policy tool to permit development but ensure that any residual adverse impacts of the development on the environment are compensated (Bull *et al*. 2013). In best practice, offsets are applied as part of a mitigation hierarchy, where all reasonable efforts to avoid or minimise impacts upon the environment are first considered (Kiesecker *et al*. 2010). Yet the limited data on the distribution and status of the northern quoll in the Pilbara, the poor understanding of critical habitat in relation to future mining and infrastructure development, as well as uncertainty around the level of impact from other threats, has meant that uncertainty around how to create direct, ecologically equivalent offsets is high. Under the Australian Government's offset policy (Department of Sustainability Environment Water Population and Communities 2012), compensatory offsets, such as directing a proportion of offset funds towards scientific research, are considered as an acceptable component of an offsets package in these situations. This has been the case for the northern quoll in the Pilbara, with approximately AU$1.75M of offset funds committed to research on the species over the next decade (although not all of this amount is currently active).

The dramatic increase in fauna surveys associated with environmental impact assessments in the Pilbara has generated a valuable dataset on the northern quoll and other threatened species (Carwardine *et al*. 2014). Collation of these data could greatly improve our knowledge of species' ranges and critical habitats, yet most of these data are not within the public domain (Carwardine *et al*. 2014). Further, it has been argued that much conservation research is having little direct influence on the achievement of on-ground conservation outcomes, in part because the conceptual novelty valued by national funding agencies may not align with the more applied needs of practitioners (Knight *et al*. 2008; Laurance *et al*. 2012). A potential solution to overcoming the 'knowledge–implementation' or 'knowing–doing' gap is to encourage collaboration between scientists, policy makers and practitioners when research projects are developed (Knight *et al*. 2008; Sutherland *et al*. 2011; Laurance *et al*. 2012). In an effort to encourage data-sharing and to foster a sense of ownership over the research agenda that will be funded by offset provisions, Parks and Wildlife instigated a collaborative process between scientists, practitioners and mining proponents to identify and rank research priorities for the northern quoll in the Pilbara. In this paper we present the research priorities, and the key questions associated with each priority, as identified by workshop participants. This is the first step in developing a research program to increase our knowledge of the northern quoll in the Pilbara, and to better understand the impacts of current and future threats, so that a viable population is maintained into the future using evidence-based management.

Methods

Parks and Wildlife hosted a workshop attended by research scientists employed in the university or government sector (13 people), research scientists and environmental consultants employed in the private sector (30 people), mining industry representatives (22 people) and representatives of Western Australian and Australian government departments responsible for environmental regulation and approvals (9 people), all of whom have knowledge of the northern quoll, mining and associated activities, and/or the Pilbara region. The workshop was facilitated by an independent, professional facilitator. The process to define research priorities was as follows: (1) After a series of presentations by experts, the group as a whole discussed the key threats to the northern quoll in the Pilbara. This included both current and future threats (e.g. climate change, cane toad invasion), and both well- and lesser-understood threats (e.g. the impact of disease). (2) Participants were then allocated to one of eight breakout groups, so that each group contained members from the range of affiliations present. Each group then identified a series of research priorities that they considered would best address the current gaps in knowledge that are the main barriers to the effective management and conservation of the northern quoll in the Pilbara, both in terms of better understanding their distribution and ecology, and in mitigating the key threats. The research priorities from each group were then presented to all participants and collated by the facilitator. (3) Each group then ranked the sequence in which the research priorities should be addressed based on which research needs they considered were most pressing. (4) The rankings were then compared and collated across groups to define the final ranking of research priorities. In most cases there was agreement across the groups as to the sequence in which the research priorities should be addressed. (5) Finally, new breakout groups were formed, based on expertise and interest, to discuss and identify the key research questions that needed to be addressed under each research priority.

Research priorities

Research priorities are presented below in the order in which they should be addressed, based on the ranking of the workshop participants. Key research questions aligned with each research priority are presented in Table 1. We also provide a brief review of the current evidence that will further guide the development of a research program to answer these questions.

Priority 1: Develop appropriate and standardised survey and monitoring methods

Developing a standard survey and monitoring protocol for the northern quoll in the Pilbara, based on detection and occupancy probabilities (Wintle *et al*. 2012), was identified as the highest research priority by the group. A review of over 200 survey reports, most of which were related to mining activities, found that the sampling effort and methods varied widely between surveys and were often not adequate to detect northern quolls (A. Cook, unpubl. data). Inadequate survey effort and/or using an inappropriate survey method introduce uncertainty as to whether the failure to detect the northern quoll within an area reflects a true absence of the species (Wintle *et al*. 2012). The data gathered from surveys that vary widely in terms of effort and method may have limited comparability, and incurs a lost opportunity to gather regional metadata for the northern quoll in an area where any survey effort represents a significant

Table 1. Research priorities for the northern quoll and key questions associated with each priority, and as compared with the information required under similar themes and the priority given to this in Woinarski *et al.* (2014)

Rank	Theme	Research priority	Key questions	Information required and priority given under similar theme in Woinarski *et al.* (2014)
1	Survey and monitoring	Develop appropriate and standardised survey and monitoring methods	• What is the efficacy of the major survey methods currently used for northern quolls in the Pilbara? How do various combinations of trap types, arrays, duration of trapping, baits, etc. compare? Which camera-trap protocol is most effective for (a) identifying individual northern quolls in the Pilbara and (b) estimating population sizes? Which method is most cost-effective and efficient in various Pilbara landscapes? • What is the detection probability of northern quolls in each habitat type? Based on prior survey, what it the prior probability of occupancy in these habitat types? Based on this knowledge, how many non-detections of quolls are required before we can state with prespecified confidence that northern quolls are absent from a site?	• Survey to better define fine-scale distribution and number of individuals in subpopulations: medium–high. • Establish or enhance monitoring program by designing integrated monitoring programs: medium.
2	Habitat requirements	Define areas of critical habitat for northern quoll in the Pilbara	• How do northern quolls use habitat in the Pilbara? How are quoll populations distributed in relation to habitat quality (e.g. high quality, low quality or sink habitats)? How is habitat selection influenced by predation risk and social factors? • What information is required to further refine an SDM for northern quolls in the Pilbara? How can this information be most effectively used to improve monitoring effort and outcomes? • How do models vary across the Pilbara mainland and offshore islands, accounting for climatic gradients and topography? • What are future predictions for northern quoll population distributions, under models of climate change and cane toad invasion?	• Assess habitat requirements: n/a.
		Understand how disturbance affects habitat quality and connectivity	• How does fire and grazing affect habitat quality and habitat use by northern quolls in the Pilbara? How important is fire as a barrier to dispersal? • How important is habitat connectivity for metapopulations of northern quoll in the Pilbara? How does habitat type affect the connectivity of metapopulations? How does disturbance, both discrete (e.g. infrastructure such as rail and roads) and diffuse (e.g. changes in vegetation composition and structure), alter habitat connectivity?	• Assess relative impact of threats: quantify relative impact of fire regimes—high. • Assess effectiveness of threat mitigation options: landscape-scale options for retention of longer-unburnt patches—high.
3	Population dynamics	Better understand the population dynamics of the northern quoll in the Pilbara	• How many subpopulations are there in the Pilbara? How do these interact? Are subpopulations demographically stable in space and time? How does habitat and climate affect population dynamics? How does disturbance affect demographic stability?	• Assess diet, life history: n/a.
		Investigate population structure and the interaction between populations	• How do measures of genetic distance relate to spatial ecology as measured by other means; i.e. does inferred genetic connectivity relate to observed dispersal? • Can genetic information be used to determine habitat barriers?	• Resolve taxonomic uncertainties: assess genetic relatedness of spatially disparate populations to identify whether there are genetically distinct subpopulations—low–medium.

4	Key threats	Introduced predators	• Does predation significantly affect the northern quoll in the Pilbara? How does this vary across habitat types? Does competition for resources with foxes or cats impact on subpopulations? Which life stages are most vulnerable? • Given that the northern quoll is also a mesopredator, does the presence of dingoes either directly (through predation) or indirectly (through the regulation of foxes and cats) impact on subpopulations in the Pilbara?	• Assess relative impact of threats: predation by feral cats and dogs—high; interactions between feral cats, dogs/dingoes and foxes—medium–high. • Assess effectiveness of threat mitigation options: assess which feasible management options for feral cats and dogs can lead to population recovery—medium–high. • Develop new or enhance existing management mechanisms for broad-scale, targeted, feral cat control—medium.
		Cane toads	• Will the closure of artificial water bodies prevent, or simply slow the rate of, invasion of cane toads into the Pilbara? • What is the degree of overlap between SDM/fundamental niche models for northern quolls and cane toads in the Pilbara? Can potential refuge areas for northern quoll be identified? • Is CTA likely to be effective when taste-aversion baits are delivered under field conditions? At what scale is bait delivery feasible?	• Assess effectiveness of threat mitigation options: assess feasibility of broad-scale taste-aversion 'training' of quolls—medium; assess local-scale exclusion of toads or prevention of colonisation (mainland sites)—medium.
		Infrastructure development and interactions with humans	• Are road-related deaths of northern quoll a significant cause of mortality in the Pilbara? • Do railway lines, infrastructure corridors or wide roads present a barrier to northern quoll movement? • What methods can be used to mitigate the impacts of infrastructure development and associated machinery operation?	• Not addressed.
		Interactions between threats	• Do frequent and intense fires lead to reduced structural complexity/loss of vegetation cover, and subsequent increased predation of northern quolls, particularly of males during and/or after breeding? • What are the cumulative impacts of mortality caused by cane toad ingestion and predation by cats, dogs/dingoes and foxes?	• See information on introduced predators and cane toads above.
5	Recolonisation of restored or artificial habitat	Determine the ability of the northern quoll to recolonise disturbed areas or colonise artificial habitat	• What are the key elements of northern quoll habitat that need to be restored/created so that habitat complexity and productivity is maximised? • What level of landscape connectivity is required around restored/artificial habitat so that genetic connectivity between subpopulations can be maintained? • How long should restored or artificial habitat be directly managed, particularly for predators? • How can the retention of large boulders of waste rock be incorporated into rehabilitation plans?	• Not addressed.

investment of time and resources. The limited amount and uncertain quality of occurrence data has been a major restriction on the utility of a species distribution model (SDM) and a population viability analysis (PVA) for the northern quoll in the Pilbara (Cadenhead *et al*. 2015; see below). While survey and monitoring *per se* is not a research activity that directly informs management or threat mitigation, carefully implemented monitoring programs are essential to identify many elements of a species' ecology, to detect changes in population, and to quantify the ecological effectiveness and cost-effectiveness of management interventions (Lindenmayer *et al*. 2013; Lindenmayer 2015).

Parks and Wildlife recently released revised protocols for the long-term monitoring of known populations of the northern quoll (Dunlop *et al*. 2014*b*), and the effectiveness of these protocols in presence/absence surveys should be tested. The cost-effectiveness of using camera traps for wildlife surveys in remote locations such as the Pilbara makes their use appealing. Hohnen *et al*. (2013) described how the strategic placement of cameras and baits combined with taking a greater number of photographs per trigger allows the capture of images that can be used to identify individual northern quolls from their spot patterns. Remote cameras have also been shown to be a viable method for estimating population sizes of the northern quoll in areas with both dense (Austin 2014) and small populations (Webb *et al*. 2015). Further testing of a range of parameters (e.g. see Nelson *et al*. 2014) to develop a robust standard protocol for the Pilbara is required, along with a comparison of the cost-effectiveness and any ethical/reduced handling benefits of using remote cameras versus live-trapping for estimating population sizes in Pilbara landscapes.

Priority 2: Improve our understanding of habitat requirements

Define areas of critical habitat for the northern quoll in the Pilbara

The Department of Agriculture and Food Western Australia has mapped 102 land systems across the Pilbara bioregion, based on several biophysical components including landform, geology, soils, vegetation and drainage patterns (Van Vreeswyk *et al*. 2004). A review of records for the northern quoll in the Pilbara showed that 65% of records were from the Robe, Capricorn and Boolaloo land systems (Table 2), which comprise low plateaux, mesas, hills and ridges of varying geology (limonite, granite and sandstone, respectively). Most recent survey effort in the Pilbara is biased towards mineral-bearing formations or areas of mining-related infrastructure (e.g. rail and road corridors) (Fig. 1). Further investigation of these records is required to assess whether these land systems are indeed preferred habitat for northern quolls, as opposed to an artefact of survey effort. The comparatively fewer records that coincide with the conservation estate in the region (Fig. 1) are also likely an artefact of survey effort.

The first step in defining areas of critical habitat for the northern quoll in the Pilbara is to improve our understanding of habitat use, particularly in terms of defining habitat suitability at finer scales than is currently available. As part of the strategic environmental assessments being undertaken for the Pilbara bioregion, an SDM has been developed for the northern quoll (Cadenhead *et al*. 2015). Uncertainty about the quality of the occurrence data available, the limited amount of data available, as well as the bias towards data collection in areas proposed for development, constrained the level of certainty around the outcomes of the model. Improved model certainty requires further collection of contemporary species-occurrence data and the development of finer-resolution GIS layers, particularly one that captures finer-scale geological attributes such as mesas or rocky outcrops, considered as highest-quality habitat for the northern quoll (Cadenhead *et al*. 2015).

Better definition of the habitat attributes favoured by the northern quoll will allow further refinement of the GIS variables included in the SDM, or allow the development of predictive, site-based habitat models. Information on how northern quolls use habitat can be gained through direct observation of how they interact with habitat features, or from the association of habitat features with the presence of quolls as determined by GPS receivers (Gaillard *et al*. 2010). This level of detail is currently not available from survey records returned as part of environmental impact assessments, but collection of habitat data using the protocols outlined by Dunlop *et al*. (2014*b*) in future surveys would rapidly increase the quality of data available.

Understand how disturbance affects habitat quality and connectivity

The alteration of fire regimes has been the most pervasive landscape-scale change in the Pilbara. Between 1993 and 2006, over 72% of the region was burnt, with more than 28% of the area burnt two or more times (McKenzie *et al*. 2009). Woinarski *et al*. (2004) found that northern quolls may be able to tolerate a moderately high frequency of fire, as long as these fires were low-intensity, early-season burns, and the impacts of fire on vegetation structure and composition were not exacerbated by the grazing of introduced herbivores. In the Pilbara, however, as with many other grazing regions of Australia, early pastoralists often overestimated the productivity and resilience of native vegetation to sheep and cattle grazing, which led to severe degradation of vegetation, particularly along river frontages (Hennig 2004). The soil degradation and loss of vegetative cover caused by intense grazing pressure in the south Kimberley is thought likely to have contributed to the substantial decline or disappearance of medium-sized animals, including the northern quoll, from the Bungle Bungle area (Woinarski *et al*. 1992). Death by predation is most likely in open areas (Oakwood 2000), and therefore the effects of fire and grazing on northern quoll populations cannot be considered without also taking account of likely increases in mortality due to predation (see 'Introduced predators' below).

Understanding how the localised but intensive activity associated with mining affects habitat quality and habitat use by the northern quoll in areas surrounding development is limited. A recent study that examined the use of ballast quarries and paired undisturbed sites by northern quolls found that they were foraging, denning and showing signs of breeding at the quarry sites, where greater numbers of quolls were captured (Dunlop *et al*. 2014*a*). This was likely due to the combination of

Table 2. Records of the northern quoll in each land system type in the Pilbara
Records were current as of 23 May 2014

Land system	Area (km^2)	No. of records	Land system description
Augustus	61	1	Rugged ranges, hills, ridges and plateaux supporting mulga shrublands and hard spinifex grasslands.
Boolaloo	1502	245	Granite hills, domes and tor fields and sandy plains with shrubby spinifex grasslands.
Boolgeeda	7748	29	Stony lower slopes and plains below hill systems supporting hard and soft spinifex grasslands and mulga shrublands.
Calcrete	1444	2	Low calcrete platforms and plains supporting shrubby hard spinifex grasslands.
Callawa	1003	9	Highly dissected low hills, mesas and gravelly plains of sandstone and conglomerate supporting soft and hard spinifex grasslands.
Capricorn	5296	257	Hills and ridges of sandstone and dolomite, shrubby hard and soft spinifex grasslands.
Coongimah	3244	12	Plateau surfaces, low hills with steep slopes and undulating uplands supporting hard spinifex grasslands.
Dune	138	1	Dune fields supporting soft spinifex grasslands.
Granitic	4020	1	Rugged granitic hills supporting shrubby hard and soft spinifex grasslands.
Horseflat	1261	4	Gilgaied clay plains supporting tussock grasslands and minor grassy snakewood shrublands.
Littoral	1577	3	Bare coastal mudflats with mangroves on seaward fringes, samphire flats, sandy islands, coastal dunes and beaches.
Macroy	13 095	94	Stony plains and occasional tor fields based on granite supporting hard and soft spinifex grasslands.
McKay	4202	21	Hills, ridges, plateau remnants and breakaways of metasedimentary rocks supporting hard spinifex grasslands.
Mallina	2557	8	Sandy surfaced alluvial plains supporting soft spinifex (and occasionally hard spinifex) grasslands.
Marandoo	459	2	Basalt hills and restricted stony plains supporting grassy mulga shrublands.
Mosquito	1840	3	Stony plains and prominent ridges of schist and other metamorphic rocks supporting hard spinifex grasslands.
Newman	14 580	81	Rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands.
Onslow	424	1	Sandplains, dunes and clay plains supporting soft spinifex grasslands and minor tussock grasslands.
Paraburdoo	565	3	Basalt-derived stony gilgai plains and stony plains supporting snakewood and mulga shrublands with spinifex and tussock grasslands.
Paradise	1479	8	Alluvial plains supporting soft spinifex grasslands and tussock grasslands.
River	4088	37	Active flood plains, major rivers supporting grassy eucalypt woodlands, tussock grasslands and soft spinifex grasslands.
Robe	865	369	Low limonite mesas and buttes supporting soft spinifex (and occasionally hard spinifex) grasslands.
Rocklea	22 993	40	Basalt hills, plateaux, lower slopes and minor stony plains supporting hard spinifex (and occasionally soft spinifex) grasslands.
Ruth	346	36	Hills and ridges of volcanic and other rocks supporting hard spinifex (occasionally soft spinifex) grasslands.
Stuart	1794	3	Gently undulating stony plains supporting hard and soft spinifex grassland and snakewood shrublands.
Taylor	129	3	Stony plains and isolated low hills of sedimentary rocks supporting hard and soft spinifex grasslands.
Talga	2124	9	Hills and ridges of greenstone and chert and stony plains supporting hard and soft spinifex grasslands.
Turee	581	2	Stony alluvial plains with gilgaied and non-gilgaied surfaces supporting tussock grasslands and grassy shrublands.
Uaroo	7681	37	Broad sandy plains supporting shrubby hard and soft spinifex grasslands.
Urandy	1311	6	Stony plains, alluvial plains and drainage lines supporting shrubby soft spinifex grasslands.
White Springs	266	4	Stony gilgai plains supporting tussock grasslands and hard spinifex grasslands.
Wona	1815	10	Basalt upland gilgai plains supporting tussock grasslands and minor hard spinifex grasslands.
Yamerina	1207	1	Floodplains and deltaic deposits supporting tussock grasslands, grassy woodlands and minor halophytic low shrublands.

habitat complexity (e.g. diversity of boulder sizes) and the presence of permanent water in the quarry, which may have increased prey availability at these sites.

Movement of animals through the landscape for dispersal and repopulation is another important consideration for a species in which both sexes tend towards semelparity, and is therefore predisposed to local extinction (Oakwood 1997). Improved understanding of how the northern quoll (particularly dispersing males) uses areas of lower habitat quality, and the identification of such habitat in habitat-suitability models, will allow future landscape-scale, strategic assessments to better predict the combined impacts of disturbance on the ability of northern quolls to move through the landscape. Analysis of regional population genetics will also improve our understanding of the level of dispersal occurring across the landscape.

Priority 3: Population dynamics

Better understand the population dynamics of the northern quoll in the Pilbara

Little information is available on the number of subpopulations of northern quoll in the Pilbara, how these subpopulations interact, how stable they are in space and time, and how they respond to disturbance. As no demographic studies have been undertaken in the region, Cadenhead *et al.* (2015) used demographic information from the Northern Territory and Kimberley populations in their PVA. Uncertainty about data quality and the limited information available on demographic parameters for the Pilbara constrained the level of certainty around the outcomes of the PVA. The model does, however, provide a framework into which new data can be incorporated as they become available. For example, preliminary data from the Pilbara monitoring program suggest that the proportion of male die-off in the Pilbara population is lower than in the Kimberley and Northern Territory populations (Dunlop, unpubl. data). Cadenhead *et al.* (2015) stress the need for more demographic and occurrence data to be collected before further development decisions are made (see 'Develop appropriate and standardised survey and monitoring methods' and 'Improve our understanding of habitat requirements' above).

Investigate population structure and the interaction between populations

Analysis of the genetic diversity and population structure of the Pilbara population of the northern quoll is ongoing. Only small differences in genetic diversity, as measured by heterozygosity, were found between samples obtained at 16 locations within the Pilbara, with the exception of the isolated population on Dolphin Island (Spencer *et al.* 2013). This result indicates a high level of movement across the landscape by individuals during mating and dispersal phases. Spatial structure analysis of samples collected from around Pannawonica suggested a 'neighbour size' of ~15 km (Spencer *et al.* 2013). Current data show no evidence of genetic bottlenecks, suggesting that if there has been a population decline in the Pilbara that this has not affected genetic diversity. A useful approach would be to combine genetic information with data from radio-tracking or GPS collars, to better understand the use of 'landscape' space and how this influences population dynamics.

Priority 4: Key threats and the interaction of these threats

Introduced predators

Introduced cats and foxes are considered to be one of the main causes of the decline and extinction of the critical-weight-range mammals (35 g to 5.5 kg) in Australia (Short and Smith 1994; McKenzie *et al.* 2007; Woinarski *et al.* 2015), but their impacts on the northern quoll are less clear. A recent review of feral cat diets across Australia found that northern quolls were present in the diet of feral cats (Doherty *et al.* 2015*a*), and Woinarski *et al.* (2014) consider the threat posed by cats to the northern quoll to be severe, although the impacts of cats may be reduced in rugged refuge areas. The impacts of cats on other, much larger, species of quoll appear to be inconsistent, with some evidence of coexistence between cats and quolls before the arrival of foxes (Glen and Dickman 2008, and references contained within). Due to the limited overlap in their distribution throughout Australia, the threat posed by foxes to northern quolls is less understood than for cats, and Woinarski *et al.* (2014) consider the threat posed by foxes to be moderate on a national level. Foxes are common in coastal, near-coastal and riparian areas of the Pilbara, and extend as far north as Broome (King and Smith 1985; Kendrick and Stanley 2002). They are renowned for their aggression towards smaller carnivores (Palomares and Caro 1999), and neither the larger chuditch (*Dasyurus geoffroii*) nor spotted-tail quoll (*Dasyurus maculatus*) are known to coexist with large numbers of foxes (A. Glen, pers. comm.). The interactions between quolls, cats and foxes are potentially more complex than for other medium-sized marsupials due to niche overlap in diet and competition for den sites, with the larger spotted-tailed quoll and chuditch both experiencing exploitation and interference competition from foxes (Morris *et al.* 2003; Glen *et al.* 2011). Competition between feral cats and the northern quoll may potentially be intense during periods of low rainfall in the Pilbara when prey availability is low. Understanding whether foxes and cats are significant predators of, or competitors with, the northern quoll in the Pilbara, and how this affects their population viability, will clarify the level of risk posed by these predators. The sausage-style baits used for feral cats (e.g. Eradicat® and Curiosity®) are potentially attractive to the northern quoll, with the risk of mortality or reduced fitness. Trials to assess the magnitude of the risks from Eradicat® baits are currently underway in the Pilbara.

The role of dingoes and wild dogs in the mortality of, and interactions between, mesopredators (both native and introduced) requires further investigation. Dingoes are known to kill northern quolls, but may not eat these kills (Oakwood 1997). A recent study in the Northern Territory found that camp dogs and dingoes were the major source of mortality for northern quolls at the study site (Webb *et al.* 2015), and roaming domestic dogs were identified as a cause of mortality for northern quolls in Queensland (Pollock 1999). Human resource subsidies (e.g. stock carrion in rangeland areas) can artificially support predator populations, thus indirectly increasing predation pressure on prey (Newsome *et al.* 2015). A dynamic debate currently exists around the role of the dingo in regulating populations of feral cats and foxes, and the implications of this for the conservation of the critical-weight-range mammals in Australia (see Johnson *et al.* 2007; Letnic *et al.* 2009; Allen *et al.* 2011, 2013; Kennedy *et al.* 2012). Understanding the population density at which the role of the dingo as a regulator of introduced predators outweighs its own impact as a direct predator of the northern quoll will inform whether dingo/wild dog control would benefit the northern quoll.

Cane toads

The introduced cane toad now occupies more than half the historic range of the northern quoll, and has caused an immediate collapse or extirpation of northern quoll populations in the areas it has invaded (Burnett 1997; Oakwood and Foster 2008; Woinarski *et al.* 2008, 2010). Earlier modelling work that considered only climate parameters, as well as more recent work that incorporates future climate change, suggest that cane toads will not invade the Pilbara (Sutherst *et al.* 1996; Pavey and Bastin 2014). Other recent work that considers the fundamental niche of the cane toad and incorporates the location of artificial watering points predicts that they will colonise the Pilbara from the Kimberley via the coastal edge of the Great Sandy Desert (Kearney *et al.* 2008; Florance *et al.* 2011;

Tingley *et al*. 2013). This has created some level of uncertainty about the likely impact of cane toads on northern quolls in the Pilbara. Strategies for cane toad management were not ranked highly by participants in the threat-management framework developed by Carwardine *et al*. (2014), which the authors explained as possibly due to uncertainty about how far cane toads will spread into the region.

The model developed by Tingley *et al*. (2013) suggested that the closure of 100 artificial water bodies at one of three potential locations along the coastal corridor between the Kimberley and the Pilbara would prevent the invasion of cane toads into the Pilbara. While their model did account for uncharacteristically wet years every three decades, the dispersal of toads between water bodies was determined by the number of rainy days occurring during the year (i.e. toads could only disperse between water bodies for three days following rainfall), rather than rainfall amount, the associated likelihood of flooding, and the availability of free water across the landscape. The cyclonic and thunderstorm nature of much of the rainfall in the north-west of Western Australia means that the region is prone to significant and sometimes extended flooding. In April 1934, the country around Anna Plains (250 km south of Broome) was flooded for hundreds of miles when 27 inches (686 mm) of rain fell in four days (Anon 1934). In March 2004, over 350 mm of rain was recorded within a 48-h period at Telfer, on the southern edge of the Great Sandy Desert, due to Tropical Cyclone Fay. This caused the flooding of the De Grey and Oakover river systems and flooded 140 km of the Telfer Access Road, with floodwaters taking several months to subside (www.bom.gov.au). Extending the model of Tingley *et al*. (2013) to account for such events will help clarify whether closing artificial water bodies is likely to prevent the invasion of cane toads into the Pilbara or may only assist in delaying their inevitable invasion.

Comparison of SDMs (e.g. Cadenhead *et al*. 2015) for northern quoll with fundamental niche models for cane toads (e.g. see Kearney *et al*. 2008) within the Pilbara may identify potential refuge areas for the northern quoll, and these areas should be prioritised for conservation actions. Because the invasion point of cane toads into the Pilbara is likely to be narrow (beginning around the mouth of the De Grey River: Tingley *et al*. 2013), a proactive approach to training northern quolls to avoid cane toads may prove beneficial. Conditioned taste-aversion (CTA) has been used successfully to train captive-reared northern quolls to avoid cane toads by offering them small, dead toads infused with thiabendazole before their release into the wild (O'Donnell *et al*. 2010). Monitoring of these quolls after their release showed that some of their offspring had learnt to avoid eating cane toads, either through ingestion of small, non-lethal toads or via social learning from their mothers (Webb *et al*. 2015). Fields trials of toad-aversion baits (either sausages or meatballs made from toad flesh and containing thiabendazole) are currently underway in the central Kimberley, where cane toads were expected to invade in late 2015 (Webb *et al*. 2015). Further testing of CTA approaches under a variety of field conditions is required. The development of stable, long-lasting baits suitable for aerial deployment is considered a pressing need, as well as a captive colony of northern quolls upon which to test the efficacy of toad-aversion baits for inducing aversion to live toads (Webb *et al*. 2015).

Infrastructure development and interactions with humans

Infrastructure development may increase the likelihood of northern quoll deaths due to motor vehicle strikes or being crushed in machinery. Significant chuditch mortality was observed along mine access roads in the south-west of Western Australia (McGregor *et al*. 2014), and the widening and sealing of an access road dramatically increased the number of road kills and led to the extirpation of the resident population of eastern quolls (*D. viverrinus*) in Tasmania (Jones 2000). Infrastructure corridors, such as high-tension power-line easements and ore-haulage railways, are increasingly being installed throughout the range of the northern quoll. Although these do not create the same mortality risk as roads, they bisect and fragment habitat, create large open spaces and potentially increase predation risk.

A recent, small-scale radio-tracking study (see Dunlop *et al*. 2014*a*) around several quarries in the Pilbara found that northern quolls crossed roads, but not railway lines. The short-term nature of this work and the limited number of quolls able to be tracked means that the influence of roads, railway lines and infrastructure corridors on the movement and mortality of northern quolls requires further assessment. Using radio-tracking techniques to determine crossing rates and road kill events may be difficult over large areas, so population studies comparing groups of quolls near major roads with those not affected by infrastructure (e.g. McCall *et al*. 2010) may provide a more feasible means of assessing the impacts of roads. If vehicle strikes are found to significantly contribute to the mortality of a local population of the northern quoll, then mitigation methods should be trialled on sections of road identified as road-kill hotspots. Culverts and underpasses have been shown to be used by a variety of small and medium-sized mammals and frogs (Taylor and Goldingay 2003), while installing rumble strips on roads has led to decreased rates of road-kill of nocturnal animals (Lester 2015).

Interactions between threats

At present, wildfire, the subsequent loss of vegetation cover and increased predation of northern quolls is likely to be the most significant of the interactions between threats. The direct effects of wildfire have been found to be less significant in the subsequent decline of small to medium-sized mammals, particularly for denning species such as the northern quoll, than the indirect consequences of reduced resource availability and the increased risk of predation due to lack of cover (Oakwood 2000; Letnic *et al*. 2005; McKenzie *et al*. 2007; Legge *et al*. 2008; Doherty *et al*. 2015*b*). Male northern quolls are perhaps most vulnerable to such losses of cover during the breeding season, when their range can extend to over 100 ha (Oakwood 2002) or, where males survive after breeding, their foraging range is extended to gain the nutrition required to recover from their poor condition (Cook 2010). Loss of cover due to late dry-season fires at East Alligator River in the Northern Territory meant little cover was available for young quolls when they began foraging, with dog and dingo predation a major source of mortality (Webb *et al*. 2015). The cumulative impacts of cane toad poisoning, fire and predation are highly likely to lead to the extirpation of small and disjunct groups of northern quoll in the Pilbara. Population viability modelling of the East Alligator River population suggested that high mortality from predation combined with late dry-season burning was preventing the recovery of northern quoll populations after cane toad invasion (Webb *et al*. 2015). Improved knowledge of the severity of these threats to northern quolls in the Pilbara, and their incorporation into the SDM and PVA framework developed by Cadenhead *et al*. (2015) will allow for better identification of priority areas for integrated cane toad, fire and predator management.

Table 3. Expected timelines for the undertaking of research under each priority over the next 10 years, and the funds currently allocated from the Pilbara Northern Quoll Offset Trust under each research priority

Rank	Theme	Research priority	Current or proposed research activity	Time over next 10 years	Current funding allocation (approximate)
1	Survey and monitoring	Develop appropriate and standardised survey and monitoring methods	• Develop monitoring protocol (traps and cameras), and investigate new methods. • Ongoing survey and monitoring in conjunction with Research Themes 2 and 3 to better map northern quoll distribution and to determine long-term population trends.	Years 1–2. Years 3–10.	$200 000 per annum over 10 years for Research Themes 1, 2 and 3 (inclusive of salaries).
2	Habitat requirements	Define areas of critical habitat for northern quoll in the Pilbara	• Identify and describe critical habitat and undertake predictive modelling of unsurveyed areas to inform further survey effort.	Years 3–4.	$50 000 for predictive modelling (Edith Cowan University)
		Understand how disturbance affects habitat quality and connectivity	• Ongoing collection of data on disturbance and habitat quality in conjunction with Research Themes 1 and 4. • Incorporation of new data into predictive models.	Years 4–10.	See above.
3	Population dynamics	Better understand the population dynamics of the northern quoll in the Pilbara	• Collect data on demographic parameters, breeding, dispersal, and home-range use to incorporate into future PVA.	Continued collection of data in conjunction with priorities 1 and 2 during years 3–10.	See above.
		Investigate population structure and the interaction between populations	• Analysis of existing tissue samples and newly collected samples.	Years 1–10.	$120 000 for initial round of genetic analysis (Years 3–5, Murdoch University).
4	Key threats	Introduced predators	• Spatio-temporal interactions between northern quolls and introduced predators. • Other projects as they arise	Years 2–4 (current PhD project, University of Queensland).	$12 000 contribution to field expenses.
		Cane toads	• Predictive modelling of cane toad distribution in the Pilbara.	Years 3–4	Part of predictive modelling by Edith Cowan University
		Infrastructure development and interactions with humans	• Investigation of impacts of linear infrastructure on northern quoll movement.	Year 4 (current Honours project, Edith Cowan University).	$15 000
		Interactions between threats	• No on-ground projects currently planned. • Potential to be assessed through PVA as data are collected under other research priorities.		No funding currently allocated.
5	Recolonisation of restored or artificial habitat	Determine the ability of the northern quoll to recolonise disturbed areas or colonise artificial habitat	• As projects arise.	Years 5–8, in collaboration with minesite restoration programs.	No funding currently allocated.

Priority 5: Recolonisation of restored and/or artificial habitat

While anecdotal evidence suggests that northern quolls will den in waste rock dumps, whether artificial or restored habitat provides for long-term population viability is not known, and long-term assessment of created habitat is required. We acknowledge that a large gap exists between the desire to use restored or artificial habitat as an ecologically equivalent offset and our limited ability to actually restore or re-create habitat that is equivalent in structure, composition and function, particularly on highly disturbed sites (Maron *et al*. 2012). Yet there is a future opportunity in the Pilbara to conduct 'natural' experiments on the recolonisation of quolls after mining ceases, including how to best design waste rock dumps so that habitat complexity and productivity is maximised by, for example, experimenting with the size and positioning of boulders, and their spatial arrangement in relation to surrounding landscape features. The use of such artificial habitat should be tested, in the first stage through direct monitoring of animals that have colonised or have been translocated to the site. Such experimentation is underway at Atlas Iron's Mt Dove operation (Atlas Iron 2012). Population modelling can then be used to predict future population sizes, rates of growth and spread, and the probability of long-term persistence in the context of various management actions (e.g. predator control: Armstrong and Reynolds 2012).

Resource allocation and timelines

While the allocation of resources and funding, and the period over which each of the research priorities was expected to be addressed, was not explicitly discussed during the workshop, the ranking of the priorities was taken to indicate the sequence in which the priorities should be addressed. At the time of the workshop, some of the research questions identified were already being investigated within various projects, and a portion of the Pilbara Northern Quoll Offset Trust allocated to these. In Table 3 we indicate the expected timelines over which some of the research programs are expected to be undertaken. While AU$1.75M has been allocated to northern quoll research in the Pilbara, it is important to note that much of this amount is not currently available, and will not become available until several approved mine developments have become operational. In Table 3 we also indicate the proportion of offset funds expected to be allocated to each research priority. Research undertaken in other regions (e.g. research into CTA in the Kimberley region ahead of the cane toad invasion front) cannot be funded from the Pilbara Northern Quoll Offset Trust, but will help address some of the research questions identified here.

Lessons learnt from the workshop process

The workshop approach used here was less formal than recent large-scale exercises used to elicit research priorities for emerging issues in science and policy at national or global levels (reviewed in Sutherland *et al*. 2011). The focus in our (much smaller) workshop was on inclusivity rather than identifying participants based on purposive sampling of expertise or organisational affiliation. We believe that the inclusive nature of the workshop was a strength, but we also recognise that this perhaps created some level of bias when ranking the research priorities. Acknowledging both the experience and knowledge requirements of those who work regularly in the Pilbara is an important component of improving the design of research programs that aim to improve conservation management in the region. Yet the research priorities and their rankings are likely strongly reflective of the current information needs of most participants, and may not align with what conservation scientists believe to be the most critical areas of research for northern quoll conservation into the future. Baseline survey and monitoring are often the first requirements of a management or research plan for the northern quoll when offset conditions are prescribed, and this was reflected in the primary ranking given to the development of standard survey and monitoring methods. We acknowledge the concern that this could simply lead to offset funding being used to 'monitor the extinction' of the northern quoll, particularly after cane toads invade the Pilbara, unless these data are used to trigger management actions (Oakwood and Foster 2008; Lindenmayer *et al*. 2013). Clearly, the currently limited information on habitat use and demographic parameters for the northern quoll in the Pilbara restricts the utility of more sophisticated research approaches such as developing robust SDM and PVA. While the severe threat that cane toads pose to the northern quoll was recognised, this threat is not immediate in the region, and may explain the less prominent ranking given to research to mitigate the impacts of cane toads.

The northern quoll has become emblematic of the dramatic and rapid species declines occurring in northern Australia, and the level of interest in this species was reflected in the high number of participants attending the workshop (one of six run by Parks and Wildlife). Given the number of attendees, better utilisation of the time available would have been gained by providing participants with a brief before the workshop, and asking them to contribute potential research questions anonymously for interactive review by other participants. In the exercises reviewed by Sutherland *et al*. (2011), questions were then discarded if they were not considered to meet criteria that were previously agreed upon. Some areas of research that gained some attention on the day may have been discarded if given greater consideration or interrogation before the workshop. For example, there was some discussion during the workshop of investigating the use of habitat surrogates to monitor the northern quoll, yet research has shown that there is little validity in using surrogates to monitor the abundance of a single species (Pierson *et al*. 2015).

Conclusions

Offset funds generated under the environmental approvals process provide an opportunity to mobilise considerable financial resources for conservation (Kiesecker *et al*. 2010). Yet there remain significant conceptual and practical limitations to be resolved to ensure that direct offsets provide measurable conservation outcomes that are ecologically equivalent to the losses sustained by proceeding with the development (Maron *et al*. 2012; Bull *et al*. 2013). The collaborative identification and ranking of research priorities undertaken here is the first step in the process of developing and evaluating potential conservation actions for the northern quoll in the Pilbara, and serves as a mechanism to ensure that the research priorities of state and federal agencies reflects the knowledge needs of practitioners and proponents currently operating in the region. The provision of offset funds over the next decade provides a unique opportunity to undertake research on a species of conservation significance at a regional scale and over a long period, through an integrated and strategic program of research rather than the collection of *ad hoc* data. While a more structured approach to defining research questions before the workshop may have led to greater critical reflection upon, and discussion of, some of the research priorities on the day, the workshop provided an opportunity for an open and diverse-ranging discussion in a collaborative environment amongst the broader community of scientists, environmental consultants and mining proponents involved in the management and conservation of the northern quoll in the Pilbara.

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