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Aerial baiting for feral cats is unlikely to affect survivorship of northern quolls in the Pilbara region of Western Australia

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Abstract

Context. Feral cats (*Felis catus*) are known predators of northern quolls (*Dasyurus hallucatus*). Management to suppress feral cat densities often uses the poison sodium monofluoroacetate (compound 1080) in baits broadcast aerially. *Eradicat*® baits have demonstrated efficacy at reducing feral cat densities in some environments. However, these are not registered for use in northern Australia because their risk to non-target northern quolls remains unknown.

Aims. We investigated the risks of aerially deployed feral cat *Eradicat*® baits containing 4.5 mg of the poison 1080 on the survival of free-ranging northern quolls.

Methods. The study was conducted over a 20 000-ha area in the Pilbara bioregion in Western Australia. Twenty-one wild northern quolls from a baited area and 20 quolls from a nearby reference area were fitted with radio-collars, and their survivorship was compared following the aerial deployment of over 9700 feral cat baits. Survivorship of quolls was assessed before and after the baiting campaign.

Key results. Five radio-collared quolls died at the baited area; four mortalities were due to feral cat predation, and the cause of one death was uncertain. At the reference area, seven radio-collared quolls were confirmed dead; three mortalities were due to feral cat predation, two from wild dog predation, and the cause of death of two could not be determined. Evidence for sublethal poison impacts on quolls, inferred by monitoring reproductive output, was lacking; average litter size was higher in quolls from the baited area than in those from the unbaited area, and within range of litters reported elsewhere, suggesting that acute effects of 1080 (if ingested) on reproductive success were unlikely.

Conclusions. Radio-collared northern quolls survived the trial using *Eradicat*® baits, and females showed no acute effects of sublethal poisoning on the basis of reproductive output. A lack of quoll deaths attributed to 1080 poisoning suggests that the use of *Eradicat*® poses a low risk to northern quolls in the Pilbara. Importantly, the high level of mortalities associated with predation by feral cats, and to a lesser extent, canids, validates the threats of these introduced predators on quolls, suggesting that their control in areas where quolls are present is likely to be beneficial for the recovery of this species.

Implications. Land managers aiming to conserve northern quolls in the Pilbara would see conservation benefits if they introduced an operational landscape-scale feral cat baiting program using *Eradicat*® baits, with appropriate monitoring.

Additional keywords: *Dasyurus hallucatus*, endangered species, *Eradicat*®, non-target species, poison bait, sodium monofluoroacetate, wild dog.

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Introduction

Northern Australia remains an important region for mammal conservation, despite the range reductions and extinctions that have occurred there (Fisher *et al.* 2014; Woinarski *et al.* 2015). In the Pilbara bioregion, for example (Thackway and Cresswell 1995), 12 species of terrestrial mammal have become extinct in the past 200 years, and another seven species have declined (McKenzie *et al.* 2007). Predation by feral cats (*Felis catus*) is a critical threat that contributes to the decline of many species of ground-dwelling medium-sized mammals (Frank *et al.* 2014; Marlow *et al.* 2015; Wayne *et al.* 2015). Woinarski *et al.* (2011, 2014) regarded predation by feral cats as an important factor affecting mammal taxa. Predation by feral cats is a listed Key Threatening Process on native wildlife species under Commonwealth legislation (Commonwealth of Australia 2015), and their effective control is a key strategy for conserving terrestrial vertebrates of conservation significance (Doherty *et al.* 2015; Woinarski *et al.* 2015). Feral cats are widespread across the Pilbara, and they are responsible for range reductions and population declines of many native animals, in particular, small to medium-sized mammals (Woinarski *et al.* 2011; Carwardine *et al.* 2014).

Sausage baits impregnated with the toxin sodium fluoroacetate (compound 1080) are now used by conservation practitioners as an effective method for controlling feral cats over large landscapes across Australia and its offshore islands (Short *et al.* 1997; Algar and Burrows 2004; Algar *et al.* 2007; Comer *et al.* 2018). The level of tolerance to 1080 by native mammals varies around Australia, depending on whether native species have coevolved with this chemical in their environment. The impact of 1080 baits on native carnivorous and other non-target mammals in south-western Australia is low because these species have evolved with several plant species that contain 1080 as a naturally occurring compound (Twigg and King 1989, 1991; Martin and Twigg 2002). However, some carnivorous native mammals may be susceptible to the poison if enough is ingested (McIlroy 1986).

Research to optimise feral cat baiting techniques has focussed on improving bait uptake by the target species (Algar and Burrows 2004; Algar *et al.* 2007; Heiniger *et al.* 2018). The *Eradicat*® bait has shown promise as being attractive to feral cats (Algar *et al.* 2007, 2013*b*). However, it may also be ingested by, and therefore a risk to, non-target carnivorous native mammal species such as quolls (King *et al.* 1989). *Eradicat*® has been an effective broad-scale method for controlling feral cats and reducing their impacts on native wildlife (Algar and Burrows 2004; Algar *et al.* 2007; Johnston 2010; Johnston *et al.* 2011, 2014). However, in its current form, *Eradicat*® may present a hazard to northern wildlife species, particularly carnivorous mammals, because of their greater sensitivities to 1080 and because of the palatability of the meat bait. In Western Australia, *Eradicat*® baits are currently registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA) for the broad-scale control of feral cats. However, there are potential concerns about the use of this bait in areas where northern quolls are present. Therefore, the bait label prohibits its use in areas where northern quolls are known to occur or within their known habitat.

The northern quoll is a carnivorous marsupial that has, in recent years, become vulnerable to several environmental changes, in particular, to the invasion of the cane toad (*Rhinella marina*; Woinarski *et al.* 2008, 2010). Once distributed widely across northern Australia, from the Pilbara, across the Kimberley and northern area of the Northern Territory, to southern Queensland, northern quolls have now contracted in range (Braithwaite and Griffiths 1994; Hill and Ward 2010). It is listed as *Endangered* under State and Commonwealth legislations, and, so, is of importance for conservation practitioners to protect. Although landscape changes due to extensive fire, land clearing, and grazing may influence range contraction for this species, feral cat impacts on northern quolls are also a concern in terms of predation and range contraction (Hill and Ward 2010; Woinarski *et al.* 2007; Hernandez-Santin *et al.* 2016). Although predation remains unquantified, it is sufficiently important to warrant research and management (Woinarski *et al.* 2014; Carwardine *et al.* 2014; Cramer *et al.* 2016).

Feral cat management often requires that baits are broadcast across large areas where these introduced predators roam. To achieve broad-scale bait delivery, aircraft have been used for deployment and this approach can achieve sustained control of feral cats at the landscape scale (Algar *et al.* 2013*a*; Comer *et al.* 2018). This method deploys 50 baits per square kilometre and results in the baits laying on the surface of the ground in an ~200 m × 40 m area, and this could pose a risk of exposure to carnivorous species such as northern quolls. The risk of aerially deployed feral cat baits, and *Eradicat*® baits in general, to northern quolls remains unresolved in a field environment, and no information on mortality rates or sublethal effects exists for this species when this bait is used.

Evidence suggests that some quoll species ingest baits deployed for wild-dog control and, so, may be at potential risk to poisoning from other baits targeting introduced predators (Murray and Poore 2004; Claridge *et al.* 2006). As a native predator, the northern quoll is at risk if it ingests toxic baits. On the basis of a 1080 LD50 of 7.5 mg/kg (King *et al.* 1989), an average-size northern quoll from the Pilbara bioregion (380–580 g) would need to ingest approximately one toxic cat bait containing 4.5 mg of 1080 to be at risk of lethal poisoning. However, captive trials can alter natural behaviours of animals and may not reflect how wild animals interact with the baits in natural conditions (Morgan and Tromborg 2007). For example, laboratory studies have shown that northern quolls remain at risk of poisoning by ingesting crackle baits containing 6 mg of 1080 used for dingo control (Calver *et al.* 1989); however, field trials have shown that dingo baits do not pose a hazard to free-ranging northern quolls (King 1989). Similarly, in a related species, the spotted-tailed quoll (*Dasyurus maculatus*), mortalities attributed to poison baiting are lower under field conditions and considered unlikely to have an impact at the population level (Körtner and Watson 2005).

The risks of toxic *Eradicat*® feral cat baits to northern quolls has not been assessed under field conditions (although see Heiniger *et al.* 2018, for risks associated with other bait types). If the risk is low, it would permit land managers the opportunity to conduct large-scale feral cat baiting programs in northern Australia without having an impact on this native species. The present paper reports on a field assessment of the risks of aerially deployed *Eradicat*® feral cat baits to a free-ranging population of northern quolls.

Materials and methods

A field bait trial was conducted under an APVMA research permit (APVMA PER14758) to assess the survivorship of northern quolls before and after a feral cat baiting program using toxic *Eradicat*® baits.

Study area

The study was undertaken at two sites in the Pilbara bioregion of Western Australia (Fig. 1) where northern quolls and feral cats co-occur, and where there was no history of feral cat baiting. Baiting occurred over a 20 000-ha area within the 163 213-ha Yarraloola pastoral lease ~140 km south-west of Karratha and 25 km south-west of the mining town of Pannawonica. An unbaited land area on the adjacent Red Hill pastoral lease, ~65 km south of the baited area, was used as a reference site; landforms and vegetation were similar to Yarraloola and are reported elsewhere (van Vreeswyk *et al.* 2004). These sites experience a semiarid climate typical of the Pilbara bioregion. Summers are hot and winters mild. Rainfall is characteristically variable, with most rain falling during January, February and March in association with tropical

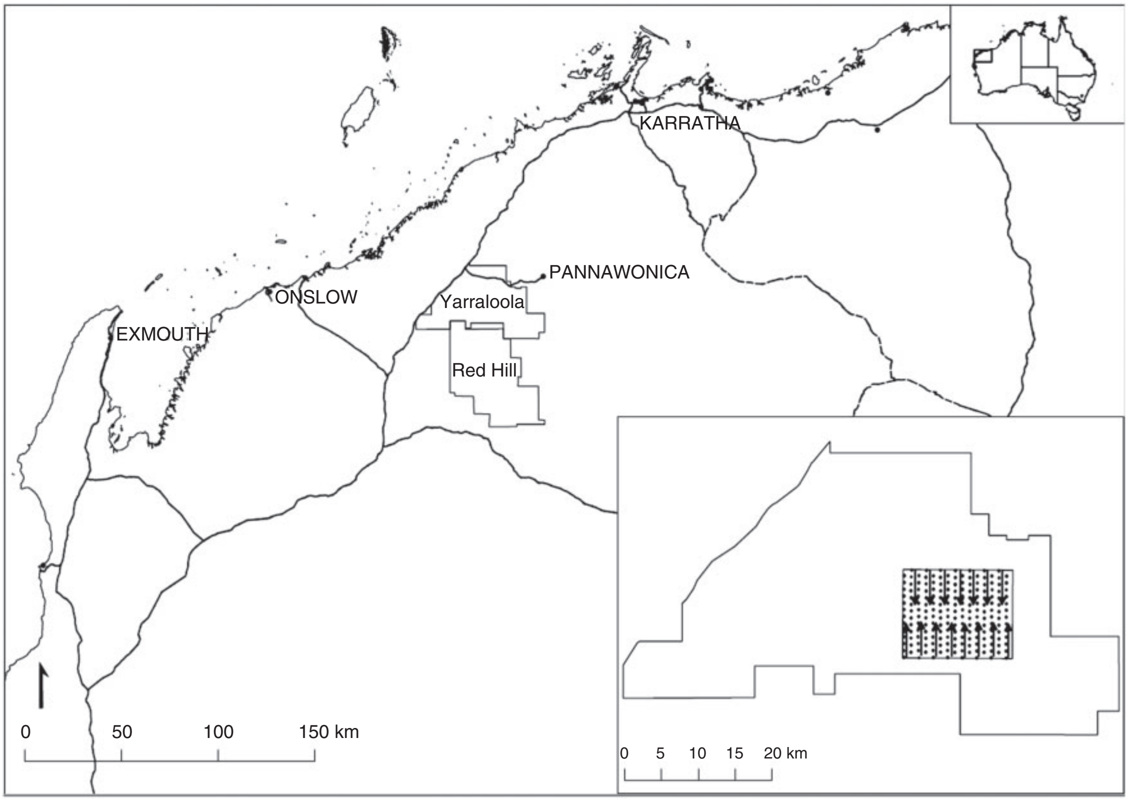

Fig. 1. Regional location of the Yarraloola and Red Hill study areas in the Pilbara bioregion of Western Australia. Inset illustrates the relative scale of the baiting cell at Yarraloola, and the locations (denoted as dots) where *Eradicat*® baits were dropped from the aircraft in July 2015, together with the flight paths of the aircraft guided by directional GPS. Forty-nine baits were dropped at each location from 500 feet above ground level.

cyclones and thunderstorm events. A second, smaller rainfall peak occurs in May and June as a result of southern frontal systems which are at their northern extent of influence over the area, interacting with moist tropical air from the north-west. The historic yearly average rainfall for Pannawonica (~25–60 km from the study areas) over 43 years is 404 mm but annual rainfall is highly variable (Australian Bureau of Meteorology). Daily temperature range is ~25–46°C in summer and 18–36°C in winter (Australian Bureau of Meteorology).

Since the 1980s, both pastoral leases have been subjected to aerial baiting once annually, together with ground hand-baiting at water points, for controlling wild dog–dingo hybrids (*Canis familiaris*/*dingo*) by using 1080 dried-meat baits. The European red fox (*Vulpes vulpes*) does occur in the Pilbara region (King and Smith 1985); however, most records are along the coast and few penetrate inland to the rocky areas. Berry *et al.* (2012) demonstrated that baiting with *Eradicat*® baits in the rangelands of Western Australia significantly reduced fox densities, and it is likely that cat baiting would also reduce fox abundance at Yarraloola if foxes were present.

Baiting risk assessment

A risk assessment plan (Department of Parks and Wildlife 2015*a*) was completed before undertaking the baiting program at Yarraloola. The assessment examined the potential risks of 1080 baiting to non-target native animals, with quolls being evaluated as the only species at risk from toxic feral cat baits. The risk to people operating in the baited area was also assessed as part of the risk-assessment process, and mitigations were implemented to reduce these risks.

Feral cat baits

Eradicat® baits (Department of Biodiversity, Conservation and Attractions Bait Manufacturing Facility, Harvey, Western Australia, Australia; Algar and Burrows 2004) were used at Yarraloola. The bait was similar to a chipolata sausage in appearance, ~20 g wet weight, dried to 15 g, blanched, and then frozen. Baits were composed of 70% kangaroo meat mince, 20% chicken fat and 10% digest and flavour enhancers (Patent No. AU781829). Each bait was injected with 4.5 mg of 1080. On the day of bait deployment, baits were thawed, and placed in direct sunlight on site. This 'sweating' process caused the oils and lipid-soluble digest material to exude from the surface of the bait. All baits were sprayed, during the sweating process, with an ant-deterrent compound (Coopex®, Bayer, Perth, WA, Australia) at a concentration of 12.5 g L^{-1} as per the manufacturer's instructions. This process aimed to prevent bait degradation by ant attack and enhanced acceptance of baits by cats, by limiting the physical presence of ants on and around the bait medium. For the present study, non-toxic rhodamine B biomarker was used to identify whether northern quolls had interacted with the *Eradicat*® baits. The rhodamine B dye was mixed through the meat ingredients during the preparation stage of the baits to equate to 50 mg per *Eradicat*® bait. Once the biomarker is ingested, the dye can mark the oral cavity, gut, internal organs and excreta (Fisher 1999). It can also be used as a systemic marker of keratinous tissue in animals (Fisher 1999). For the present study, we used rhodamine B as a tracer dye by visually inspecting the animal's oral cavity, paws and excreta under ambient light for any staining.

Prebait trapping and radio-collar deployment

During the drier, cooler months of May to June 2015, northern quolls were trapped at Yarraloola and Red Hill by using linear transects of varying numbers (between 10 and 50, depending on the environment) of small Sheffield cage traps (170 × 170 × 460 mm; Sheffield Wire Co., Welshpool, Western Australia, Australia), each baited with a mixture of peanut butter, oats and sardines. Traps were set at ~25-m spacing over a maximum of four consecutive nights at any single location, placed in sheltered, shady locations, and covered with a hessian bag to protect trapped animals from the heat. Trap lines ran along the footslopes or on top of rocky breakaways and mesas, as well as in and around gorges.

All trapped quolls were weighed, measured and sexed, and a small tissue biopsy was taken from each ear for DNA analysis. Each animal was individually marked with a passive implant transponder (PIT) tag (Allflex Microchips Australia Pty Ltd, Melbourne, Vic., Australia) inserted subcutaneously between the shoulder blades.

At both sites, adult quolls weighing between 300 and 790 g were fitted with VHF collar radio-transmitters equipped with a mortality mode, such that the radio-collar weight was no more than 3–5% of the bodyweight (Sirtrack, Havelock North, New Zealand). These radio-collars were initially tasked with operating only during daylight hours (~0600 hours to 1800 hours) to prolong battery life to 6 months. The mortality sensor was set for activation if the collar remained stationary for at least 12 h; after this time, the pulse rate doubled. Quolls were released at their site of capture at least 15 days before the commencement of baiting at Yarraloola.

There were issues with receiving signals from quolls located in daytime refuges within rock piles and mesas. Signals were often weak, intermittent, highly directional and exceptionally short range, making it difficult to accurately locate quolls during the day. Radio-collars were, therefore, programmed to commence emitting signals later in the day (0900 hours to 1000 hours) and extending into the evening (2100 hours to 2200 hours); this was more efficient to pick up signals to locate quolls because they were active and roaming at night. Note that we did not use global positioning system (GPS)/VHF radio-transmitters because these were not small enough and were quite expensive at the time, likely to influence quoll behaviours, and unlikely to receive ethics approvals because of an imbalance in quoll weight : collar weight ratios.

The movements of quolls were monitored before baiting commenced by using ground and aerial radio-tracking. Locational fixes of individuals were attempted daily over a 4-week period (June–July 2015). Radio-tracked quolls also provided information on habitat use, size of home range, and linear distances travelled (between locational fixes). Home range was estimated using the convex-hull method (Worton 1995).

Feral cat aerial-baiting operations

Baiting at Yarraloola took place on 6 July 2015 under permit (No. 423/4/15), following guidelines on the use and management of 1080 (Department of Parks and Wildlife 2015*b*), the Code of Practice for the safe use and management of 1080 in Western Australia (Department of Health 2012), and the associated risk assessment (Department of Parks and Wildlife 2015*b*).

Because our study was undertaken over a small area, we did not assess the efficacy of *Eradicat*® baiting for controlling feral cats. However, elsewhere in the Pilbara (e.g. Fortescue Marsh), feral cat baiting using the same bait and over larger areas (>100 000 ha) has demonstrated significant declines in occupancy of this introduced predator (Comer *et al.* 2018).

The timing of baiting was selected to coincide with the coolest and driest period for the study area (July) when bait uptake by feral cats is expected to be maximised owing to a low abundance and activity of prey items, in particular, reptiles (Algar and Burrows 2004). Bait degradation related to high rainfall, ants and hot weather is also significantly reduced at this time, thus prolonging bait attraction to feral cats (Algar *et al.* 2007). This timing was also at a time of year when male northern quolls were highly mobile as they searched for mates, when first-year quolls would be reproductively active, and when females would be gaining weight in readiness for pregnancy and pouch young (Oakwood 2000).

Baiting was conducted from a dedicated baiting aircraft and followed predetermined and approved transects (Fig. 1). The actual flight path was logged by the plane GPS. Baiting prescriptions required bait deployment in batches of 50 per km intervals. Previous trials showed that the ground spread of 50 baits will be ~200 × 40 m (Algar *et al.* 2013*a*). Flight lines were one kilometre apart and covered the entire bait cell. The aircraft flew at 280 km h^{-1} and 500 feet above the ground level. A GPS point was recorded on the flight plan each time a batch of 50 baits left the aircraft.

Monitoring following baiting

Immediately following bait deployment, ground radio-tracking continued (where possible) daily and aerial tracking twice over a 12-week period to October 2015, to assess the survivorship of the radio-collared quolls. The baiting coordinates recorded from the aircraft were superimposed with location fixes of radio-collared quolls to determine the likelihood that an individual would have had the opportunity to encounter baits.

Dead quolls were detected using mortality signals from the transmitters. Carcasses were retrieved as soon as possible and examined to determine the cause of death, when possible. Where predation was suspected to play a role in the death of a quoll, the retrieved radio-collars and associated tissue were placed in plastic bags and kept in a freezer before DNA analysis, by using the approach of Berry *et al.* (2012) to determine the most likely predator associated with the carcass and potentially being responsible for the death. Where there was no evidence of predation, individuals were visually examined externally for the presence of the rhodamine B biomarker within the first

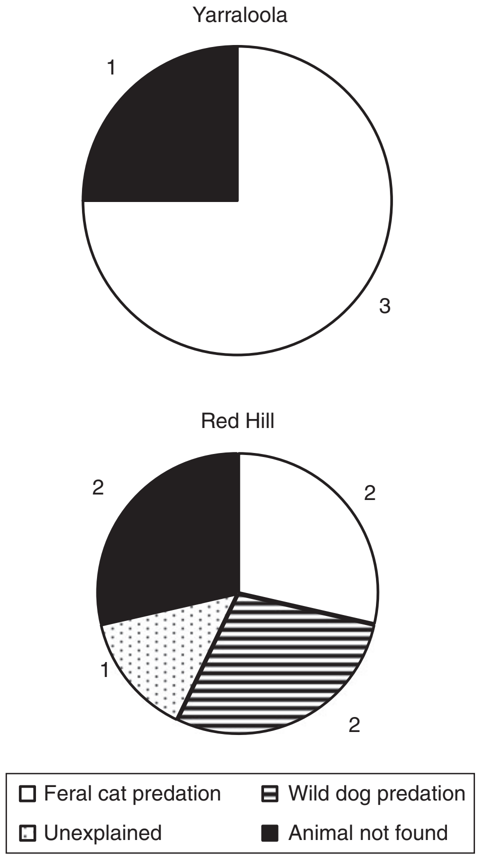

Fig. 2. Proportional cause of mortality or fate of radio-collared northern quolls at Yarraloola and Red Hill following 1080 baiting at Yarraloola on 6 July 2015. Values represent numbers of individuals.

2 weeks following bait deployment, when the dye was expected to remain.

Trapping recommenced 7 days after bait deployment at Yarraloola (44 days combined in July, August, September and October 2015), and on 1 August at Red Hill (37 days combined in August, September and October 2015). The objective of trapping was to retrieve radio-collars, assess quoll health and reproductive status, and to confirm the survival of individuals when location of individuals by radio-tracking had been unsuccessful. Trapping in September and October was undertaken to establish baseline data for a series of long-term monitoring sites. This also enabled us to assess whether breeding was occurring (presence of pouch young). Reproductive success was defined by the proportion of female adults with pouch young.

Northern quoll survivorship

The impact of feral cat baiting on northern quolls was assessed by comparing quoll survivorship at the Yarraloola (baited) and Red Hill (unbaited) sites, before and after bait deployment at Yarraloola. Because the focus of our study was on non-target impacts (to northern quolls), we do not report on the effect of aerial baiting on the local feral cat population. Survivorship was determined by monitoring radio-collared quolls at each site. The body mass of captured quolls, and evidence of reproductive success in females, were also assessed as measures of survivorship and the impact of baiting.

Results

Bait delivery rates

A total of 9750 *Eradicat*® baits was delivered at an application rate of 49 baits per km^2, which is slightly lower than the prescribed rate of 50 baits per km^2. Bait-drop locations were evenly spread across the bait cell (Fig. 1).

Northern quoll prebait trapping

At Yarraloola, 1838 trap-nights resulted in the capture of 60 quolls (3% trap success), comprising 21 individuals (10 females, 11 males). At Red Hill, 37 quolls were captured over 687 trap-nights (5% trap success) comprising 20 individuals (10 females, 10 males). All were fitted with radio-collars.

Two radio-collared quolls (one female, one male) died at Yarraloola 1–18 days before the feral cat baiting operation. Following DNA analyses of the collars, the causes of death were assessed as predation from feral cats. Two radio-collared female quolls died at Red Hill 33–34 days before baiting at Yarraloola; the cause of death of one quoll was attributed to feral cat predation; however, the cause of death of the second quoll was unknown because the collar was in a cavity beneath rocks and was not retrievable.

Weather conditions before and during bait deployment

Heavy rainfall may affect the attractiveness of *Eradicat*® baits to target (and non-target) species (Algar *et al.* 2013*b*). In the present study, weather conditions before, and on the day of, baiting were dry. However, rainfall at Pannawonica, ~25 km from the study area, was 0.2 mm on 12 July (6 days after baiting) and 11.8 mm on 22 July (16 days following baiting).

Northern quoll survivorship following feral cat baiting

At the time of feral cat baiting at Yarraloola, 19 radio-collared northern quolls remained alive. Following baiting from 13 July to 16 October 2015, there were 106 captures of 30 individual quolls (18 males, 12 females). All quolls that could be located at the time of baiting were recaptured at least once up to mid-October when monitoring for the present study ceased. Captures included 17 radio-collared individuals, and also 13 uncollared (new capture) quolls. No evidence of rhodamine B exposure was observed on live individuals, and no individual exhibited symptoms of 1080 poisoning. Three radio-collared quolls (two females, one male) died. Quolls were recovered from drainage lines 2 days and up to 73 days following feral cat baiting. Decapitation, evidence of teeth marks on the radio-collar, together with DNA analysis for two quolls to confirm the cause of death, associated feral cats with the kill of all three quolls (Fig. 2). A fourth (male) quoll was not able to be located and, so, it remained unknown whether the radio-collar failed, or the animal moved a long distance from the site. The remaining 15 radio-collared quolls survived, and their collars were successfully removed.

At Red Hill, 18 radio-collared quolls were alive during the time when Yarraloola was baited. Following baiting from 1 August to 16 October 2015, there were 103 captures of

Table 1. Summary data representing the number of northern quolls radio-collared at Yarraloola and Red Hill during the study period

Parameter	Yarraloola (baited)			Red Hill (unbaited)		
	Males	Females	Total	Males	Females	Total
Number of quolls radio-collared	11	10	21	10	10	20
Litter size (mean ± s.e.)		7.2 ± 0.3 ($n = 10$)			5.3 ± 0.5 ($n = 8$)	

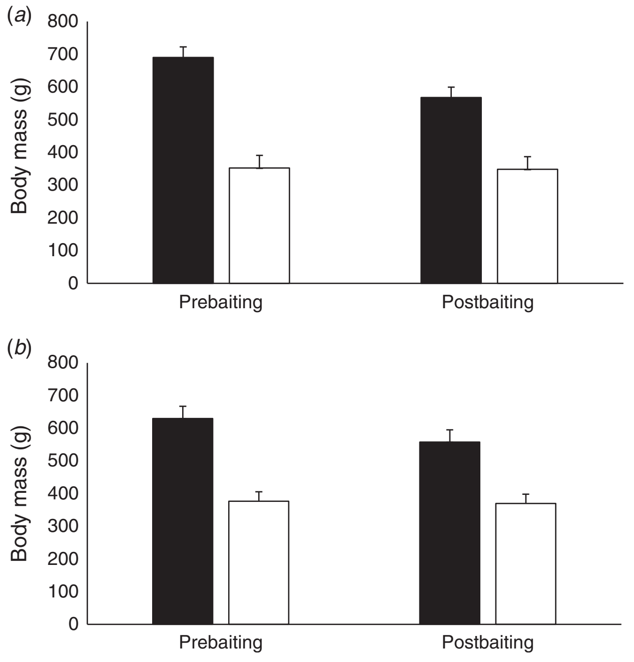

Fig. 3. Body mass of radio-collared male (dark bars) and female (open bars) northern quolls at the (*a*) baited study area, Yarraloola ($n = 8$ males, $n = 8$ females), and (*b*) unbaited study area, Red Hill ($n = 5$ males, $n = 7$ females), before (May) and after (August–October) baiting. Values are mean (s.e.).

31 (14 females, 17 males) individuals in 1523 trap-nights (7% trap success rate) across 18 locations. Seven radio-collared quolls died or were unaccounted for. Similar to Yarraloola, quolls were recovered from drainage lines 2 days and up to 66 days following the bait deployment at Yarraloola. Four deaths were attributed to predation, including two associated with feral cat predation, and two with canid predation (Fig. 2). No cause of death could be assigned to one quoll because the carcass was deep within a rocky breakaway and could not be recovered. Two male quolls were not located, and it is unknown whether the radio-collar failed, or the animal moved a long distance from the site. The remaining 11 radio-collared quolls survived, and their collars were successfully removed.

Northern quoll reproduction following feral cat baiting

At Yarraloola, pouch young first appeared in late August. Of 12 adult females trapped from August to October, 10 had pouch young and the litter size was 7.2 ± 0.3 (mean ± s.e.) pouch young per female (Table 1). Body mass of males was significantly ($t_{17} = 8.01$, $P < 0.001$) higher than that of females before and after baiting (Fig. 3*a*). The mean body mass of females was the same before and after the baiting.

At Red Hill, pouch young first appeared slightly later, in early September. Fourteen females were trapped and eight had pouch young. The litter size was 5.3 ± 0.5 (mean ± s.e.) pouch young per female (Table 1), which is a significantly lower figure than the average litter size at Yarraloola ($t_{12} = 3.40$, $P = 0.005$). Similar to Yarraloola, mean body mass of males was significantly ($t_{16} = 5.00$, $P < 0.001$) higher than that of females (Fig. 3*b*), and female body mass remained similar throughout the study.

Northern quoll locations in relation to baiting area

At Yarraloola, male home ranges were estimated from an average of 15 radio-fixes per quoll, and female home ranges were estimated from an average of 13 radio-fixes per quoll. Male home ranges averaged 931 ha (Table 2) and overlapped with 8.5 ± 1.8 (mean ± s.e.) bait-drop locations. Females had significantly smaller mean home ranges (33 ha) and shorter linear movements (1.0 km) than did males (6.7 km), and were estimated to overlap with 0.6 ± 0.2 (mean ± s.e.) bait-drop locations.

At Red Hill, male home ranges averaged about one-third of those recorded for males at Yarraloola (Table 2). Similarly, linear movements averaged 3.3 km, which is about half that recorded for males at Yarraloola. Although female home ranges were ~43% smaller in area than those reported at Yarraloola, average linear movements remained comparable between the locations (Table 2). Similar to Yarraloola, male home ranges at Red Hill, and linear movements, were higher than those of females.

Discussion

The present baiting trial has been the first to examine the impact of *Eradicat*® feral cat baits on the survivorship of northern quolls under field conditions. Despite captive studies and desktop risk assessments suggesting that a single *Eradicat*® bait contains enough 1080 to kill a northern quoll, and despite evidence from camera images that quolls may find and pick up baits (R. Palmer, unpubl. data), we found no evidence that radio-collared free-ranging northern quolls consumed aerially distributed baits, or died, as a result of the baiting program. In addition, uncollared (new) quolls that were captured at Yarraloola following bait deployment showed no acute symptoms of poisoning. Taken together, we consider that the use of aerially broadcast *Eradicat*® baits during the Austral winter months is unlikely to have a population-level impact on free-ranging northern quolls in the Pilbara.

Replicate trials over larger areas, at different arid sites and in different seasons, are warranted to add further weight to our conclusion. The dry conditions before, and up to 6 days following, bait deployment suggests that rainfall is unlikely to have been a factor reducing bait palatability by feral cats or quolls. Longer-term monitoring of the northern quoll populations at

Table 2. Home-range size (convex hull) and linear movements of northern quolls with radio-collars at Yarraloola and Red Hill
Values represent mean (±s.e.)

Parameter	Yarraloola		Red Hill	
	Males	Females	Males	Females
Home range (ha)	931.1 ± 259.9	32.5 ± 10.7	301.4 ± 108.9	13.8 ± 6.6
Linear movements (km)	6.7 ± 1.8	1.0 ± 0.1	3.3 ± 0.6	0.8 ± 0.1

Yarraloola and Red Hill following annual *Eradicat®* baiting over most of Yarraloola (147 000 ha) have been under way since 2015; preliminary results have shown continued and improved survival of northern quolls in the landscape (Palmer and Anderson 2018).

The findings from the field trial were similar to those from bait-uptake studies on free-ranging quolls elsewhere in Australia that demonstrated negligible impacts on this species group (King 1989; Körtner *et al.* 2003; Morris *et al.* 2003; Cremasco 2005; Körtner and Watson 2005; Claridge *et al.* 2006; Algar *et al.* 2017). For example, spotted-tailed quolls under free-ranging conditions showed that some individuals tested positive to the rhodamine B biomarker following aerial deployment of standard meat baits for wild dogs; however, the majority survived (Körtner and Watson 2005; Claridge and Mills 2007; Körtner 2007). Meat baits have been shown to be palatable to northern quolls; on Groote Eylandt, for example, a high proportion of northern quolls ingested (non-toxic) meat baits during field trials, suggesting that the bait medium was sufficiently attractive to eat (Heiniger *et al.* 2018). Assuming the meat in the *Eradicat®* bait is also sufficiently attractive to northern quolls, it remains unclear why we did not record quoll deaths during our trial.

The mechanisms that may have allowed quolls to persist are worth exploring. Quolls may have survived for reasons such as total bait rejection, partial ingestion and/or bait regurgitation. No live quolls were found with evidence of rhodamine B, although the biomarker may not have been visible if quolls ingested a small amount of bait. Studies on bait-aversion trials have suggested that northern quolls learn to avoid poor-tasting foods following initial ingestion (Indigo *et al.* 2018). Such a learned feeding behaviour may be associated with the ability to taste 1080, as has been reported in other marsupials (Morgan 1982; Sinclair and Bird 1984; Calver *et al.* 1989; O'Connor *et al.* 2005). Sublethal exposure to 1080 may contribute to (primarily) female northern quolls learning to avoid *Eradicat®* baits, as has been reported for spotted-tailed quolls (Körtner 2007). Annual dog baiting occurs across the Pilbara, so historical exposure of northern quolls to meat baits at Yarraloola may have predisposed animals to avoid ingesting *Eradicat®* baits, although we think this is unlikely; work by King (1989) suggested that northern quolls are not affected by aerially broadcast poisoned dog baits. Furthermore, dog baiting occurred in September of 2015, after the cat baiting, so that few, if any, male quolls (following male die-off) and few (2–3-year-old) females would have been pre-exposed to wild-dog baits deployed previously. Regurgitation is a common reaction in carnivorous mammals exposed to 1080 (McIlroy 1981), although it is difficult to understand how this reaction might behaviourally or physiologically evolve. We found no evidence from captured animals that quolls ingested, or regurgitated, *Eradicat®* baits they had encountered. In a subsequent camera-trap study, Palmer *et al.* (2017) confirmed that some northern quolls do pick up baits, and nibble and/or regurgitate *Eradicat®* baits, suggesting a learned behavioural response to bait palatability.

We suspected that northern quolls at Yarraloola, particularly males, had opportunities to consume feral cat baits during our study. Males were highly mobile over large areas, particularly during the mating months of June–July, increasing their chance of locating baits. Average recorded home ranges for males overlapped with approximately eight bait-drop locations. Female home ranges were comparatively smaller; however, we suggest that individuals were likely to be exposed to baits because of their capacity to move over scales of 1 km, distances that were similar to bait-drop intervals.

Our results, like other studies on quolls in southern Australia (Körtner and Watson 2005; Claridge and Mills 2007), cannot distinguish between individuals that ingested and regurgitated baits, and those that avoided baits. We also could not identify evidence for sublethal dosage that may have occurred following partial or whole ingestion of baits. Individuals at Yarraloola that may have been exposed to a sublethal dose of poison would be expected to experience secondary chronic effects of poisoning and later die, or females may pass toxins into milk reserves that can kill the pouch young (McIlroy 1981). Sublethal doses of 1080 can also potentially cause sterility in males as demonstrated in rats (Sullivan *et al.* 1979). Comparing measures of litter size and body mass of individuals in our study to those of northern quolls elsewhere suggests that northern quolls were unlikely to have suffered sublethal doses following ingestion of baits. The litter size for quolls at Yarraloola was significantly higher than that recorded for northern quolls at Red Hill, and within the size range of litters recorded in the Pilbara (5–7 per female; Dunlop *et al.* 2016), and elsewhere in their range (e.g. Kakadu, Northern Territory 7.3 ± 0.3 pouch young per female; Oakwood 2000). Furthermore, quoll body mass before and after baiting remained within variance of those recorded for northern quolls elsewhere in the Pilbara (Dunlop *et al.* 2016). Finally, no evidence of the rhodamine B biomarker was found in radio-collared carcasses, on live animals, or in the scats of live quolls. We, therefore, consider the likelihood that quolls ingested a sublethal dose of the 1080 poison from baits to be low, with no evidence for an impact on litter size during our study.

We consider it to be highly unlikely that 1080 was directly involved in the fate of one male quoll at the baited site. Radio-tracking showed that this individual was active at least 43 days following baiting, which is well outside the times reported for 1080 poisoning (1–17 days) following ingestion (McIlroy 1981). Whether this individual died as a result of post-mating male-die off is unknown but conceivable, given the time of year it occurred. We, therefore, conclude that this individual is likely to have survived the baiting.

The impact of feral cats on northern quolls at both study areas was higher than that reported elsewhere in Australia. For example, in the tropical savannas of northern Australia, Cook (2010) found no quoll deaths associated with predation by feral cats, and Oakwood (2000) reported that 6% of quolls were predated on by feral cats. In our study, at least 80% of the radio-collared quolls at Yarraloola, and one-third (33%) at Red Hill, that died were predated by feral cats over a period of 6 months. These predation events were a primary cause of mortality of adult quolls at both sites, and were likely to be a reflection of predicted higher feral cat densities in the arid and semiarid regions of Australia than in the wetter northern tropical areas (Legge *et al.* 2017).

Many of the dead quolls predated by feral cats were recovered from drainage lines. Hernandez-Santin *et al.* (2016) found positive associations between quolls and their distance to creek lines, suggesting that quolls face considerable predation risks when they use these corridors to traverse open landscapes between rocky areas. Population viability models suggest that even small (>5%) increases to juvenile mortalities above current levels may double the risk of extinction of local populations (Moro *et al.* 2019). We suggest that, in northern Australia, feral cat predation, coupled with dog predation events, are important and unquantified triggers that increase the risks of local quoll extinctions in an area more so than the unlikely effects of *Eradicat*® baits. Feral cat predation on northern quolls highlights the value of implementing landscape-scale feral cat control in the Pilbara. Ongoing canid control would also benefit quolls in this and similar environments.

The results of the present study have provided managers with some confidence that *Eradicat*® poison baits used to reduce feral cat abundance during the cool, dry months of the year in northern Australia are unlikely to pose a significant risk to northern quolls. However, we acknowledge that our interpretation of the results from our trial needs to be placed within the context of the experimental design; the scale of our study was limited to one operational trial area and one reference area for reasons associated with managing the logistics and costs of this project, and, therefore, lacked replicates. Regardless, the extension of the present trial into a larger operational cat-baiting program at Yarraloola 2016–2019 should provide further evidence of the benefits of cat baiting to northern quoll conservation. We suggest that the impacts that feral cats have on northern quolls outweigh any direct or sublethal risks that *Eradicat*® baits may pose to this species. Importantly, we have direct evidence of high predation events of feral cats on a northern quoll population during our study, highlighting the importance of controlling feral cats in the Pilbara so as to prevent further declines of native fauna. Managing a landscape for feral cats is likely to be of high conservation benefit to this threatened marsupial, with benefits manifesting to other fauna threatened by introduced predators (Woinarski *et al.* 2014). We recommend that where the management of feral cats is considered a necessity for the conservation of ground fauna in northern Australia, and where northern quolls are likely to occur, conservation practitioners consider the use of *Eradicat*® feral cat baits, with a biomarker to assess evidence of uptake, in conjunction with continued monitoring of quolls and introduced predators.

Conflicts of interest

The authors declare no conflicts of interest.

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