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First in, first served: uptake of 1080 poison fox baits in south-west Western Australia

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Abstract

Context. In Western Australia, baits containing 1080 poison are widely used to control the red fox (*Vulpes vulpes*) for fauna conservation. Despite long-term (15–17 years) baiting programs, bait uptake by target and non-target species is largely unknown, but affects baiting efficacy.

Aims. We examined bait uptake of 1080-poisoned fox baits laid according to current practice at seven riparian sites in the northern jarrah forest (of south-west Western Australia). There, intensive baiting regimes have been implemented for the protection of quokka (*Setonix brachyurus*) populations.

Methods. Over 9 months, 299 Probait® baits were monitored regularly to determine their persistence, and, at 142 of these, Reconyx HC500 remote cameras were used to identify the species taking baits. To compare bait uptake with species presence at these sites, we calculated an activity index for each species from the number of passes of animals in front of the cameras.

Key results. The species taking baits was identified for 100 of the baits monitored with cameras, and, because of multiple species taking baits, 130 bait take incidents were recorded in total. The fate of 40 of the baits was not discernible and two baits were not removed. In all, 99% of baits monitored by cameras were taken by non-target species and quokkas took 48% of them. The majority of baits (62% of the total 299 monitored) were taken before or on the first night of deployment, and 95% of baits had been taken within 7 days. With the exception of feral pigs, which took more baits than predicted from their activity index at these sites, baits were taken in proportion to the activity index of species. Foxes were present at four of the seven sites, but only one fox was observed taking a bait.

Conclusions. The high level of uptake of baits by non-target animals reflects their diversity and abundance at these sites, but also significantly reduces the availability of baits to control foxes.

Implications. Strategies to reduce non-target bait uptake and increase bait availability for foxes are required.

Additional keywords: fox baiting, Reconyx HC500, remote cameras, sodium fluoroacetate, threatened species.

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Introduction

The control of introduced predator species is a significant conservation issue globally (Côté and Sutherland 1997; Yerli *et al*. 1997; Harding *et al*. 2001). Ten years ago, it was estimated that the control of the European red fox (*Vulpes vulpes*) in Australia cost A$16 million, whereas losses to livestock industries were estimated to cost A$208 million, where estimates were based on only a 3% lamb mortality rate (McLeod 2004). Environmental impacts are even more difficult to value (Saunders *et al*. 2010). These estimates put fox control at the top of the list of costs incurred as a result of introduced vertebrate pest species in Australia.

Red foxes are well established across the southern two-thirds of the Australian continent and have been implicated in the decline of many Australian species (Saunders *et al*. 2010). Following their introduction to eastern Australia in the mid-1800s, red foxes had spread to Western Australia by the 1920s (Jarman 1986), a time when many native species had already suffered declines and range contractions, most likely as a result of disease, and the compounding effect of fox predation resulted in a further decline and loss of species (Abbott 2006, 2008). The instigation of broad-scale fox control in the 1980s probably prevented the extinction of some native species (Abbott 2008). Because monitoring of fox numbers themselves is too difficult (because of low trappability), historically, observations of native prey species response following fox-control efforts have been used as evidence for the impacts of foxes. Marked increases in native populations at specific sites within the south-west forests were observed for native fauna (e.g. woylies or brush-tailed bettongs *Bettongia penicillata*, southern brown bandicoots *Isoodon obesulus*, brush-tailed possums *Trichosurus vulpecula hypoleucus*, chuditch *Dasyurus geoffroii* and rock-wallabies *Petrogale lateralis*) following intensive 1080 baiting for foxes (Kinnear *et al*. 1998, 2010; Burrows and Christensen 2002). In addition, the success of reintroduction programs has been strongly linked with predator control (Short *et al*. 1992), with the exclusion of predators (foxes, feral cats, *Felis silvestris catus*, and dingoes, *Canis lupus dingo*) greatly increasing survival of native species (Risbey *et al*. 2000; Moseby *et al*. 2009*a*; de Tores and Marlow 2012).

Unfortunately, intensive methods for controlling foxes (e.g. shooting, den fumigation and trapping) are labour intensive and costly, and consequently, tend to be restricted to small areas (Saunders *et al*. 1995). The most commonly used fox-control technique is lethal baiting (Saunders *et al*. 2010). Broad-scale fox control in Australia usually involves poison baiting with compound 1080 (sodium monofluoroacetate) in a range of presentations, e.g. meat injected with poison, commercial Foxoff® baits and Probait® sausages (Saunders *et al*. 2010). Meat has been the preferred substrate for baits because of its palatability to foxes and arguably high target specificity (Kinnear *et al*. 1988). Greater baiting efficacy is possible when targeting naïve fox populations (i.e. animals not previously exposed to persecution and/or baiting, and/or consisting of predominantly yearling dispersers) (Thomson and Algar 2000; Thomson *et al*. 2000). A review of fox-control programs in Australia (Saunders and McLeod 2007) indicated red fox population reductions of between 50% and 97% as a result of various baiting protocols.

In Western Australia, many native fauna species have an increased tolerance to 1080 as a result of coevolution with *Gastrolobium* and *Oxylobium* plant species that contain a natural form of fluoroacetate (King *et al*. 1978; McIlroy 1986; McIlroy and King 1990; Twigg and King 1991). Consequently, in Western Australia, 1080 is widely used for the control of red foxes, including the broad-scale aerial deployment of large numbers of baits. In 1996, the Department of Conservation and Land Management (CALM) (now Parks and Wildlife, DPaW) began 'Western Shield', a pioneering initiative involving the aerial deployment of over 800 000 1080-injected meat baits seasonally over 3.9 million hectares of DPaW-managed land throughout south-west of Western Australia for the control of foxes (Department of Conservation and Land Management 1996; Armstrong and Batini 1998; DPaW 2013). Targeted ground-baiting is also conducted in reserves of conservation significance smaller than 20 000 ha (Department of Conservation and Land Management 1996). For example, targeted ground-based bait deployment in riparian zones in the northern jarrah forest has been carried out to protect known populations of mainland quokkas (*Setonix brachyurus*) (Hayward 2002).

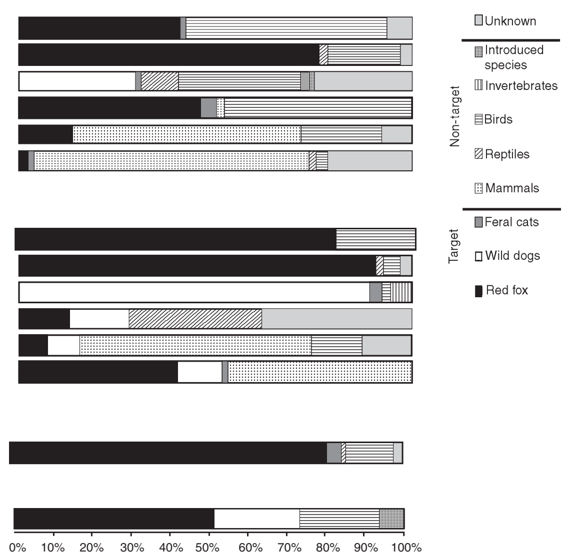
Despite extensive and long-term baiting programs in Western Australia, information on the species taking 1080 baits is limited. The results of eight Australian studies that identified species bait take have been summarised (Table 1). Birds appear to be the primary non-target group responsible for taking baits laid on the surface (Thomson and Kok 2002; Marlow *et al*. 2008; Moseby *et al*. 2011). Target foxes and dogs take a greater proportion of buried baits (Table 1, and references therein). There also appears to be a link with habitat type, which is likely to also reflect animal presence; although there is greater uptake of baits by foxes in agricultural areas (e.g. Thomson and Kok 2002), the higher incidence of non-target species taking baits in mixed and open forests (e.g. Allen *et al*. 1989; Moseby *et al*. 2011) may simply reflect a greater diversity and abundance of wildlife in native vegetation sites than in agricultural lands.

Table 1. Published studies reporting bait-uptake rates by target and non-target species in Australia

Values have been recalculated from the original publications and include only baits that were known to be taken or eaten (i.e. visited baits excluded). Bait type: DM = dried meat; FM = fresh meat; EC = Eradicat®; PB = Probait®; FO = Foxoff®; DF = Defox®. Bait toxicity: T = toxic, NT = non-toxic). Habitat: SU = semi-urban; AG = agricultural; AR = arid zone; MFA = mixed forest with agricultural; MF = mixed forest; RG = rocky gorge; OF = Open forest; JF = jarrah forest

Presentation	Bait type	Toxicity	Habitat	Number of baits	Reference
Surface					
	DM	T	AR	64	(Moseby *et al*. 2011)
	DM	NT	AG	144	(Thomson and Kok 2002)
	FM	NT	MFA	649	(Allen *et al*. 1989)
	EC	T	AR	48	(Moseby *et al*. 2011)
	PB	NT	OF	39	(Marlow *et al*. 2008)
	PB	T	JF	61	(Wayne *et al*. 2011)
Buried					
	DM	T	AR	10	(Moseby *et al*. 2011)
	DM	NT	AG	109	(Thomson and Kok 2002)
	FM	NT	MFA	38	(Allen *et al*. 1989)
	FM, FO, DF	T	RG	943	(Woodford *et al*. 2012)
	FO	T	MF	106	(Glen and Dickman 2003)
	FO	T	MF	156	(Körtner *et al*. 2003)
Tethered					
	DM	NT	AG	274	(Thomson and Kok 2002)
Surface and tethered combined					
	PB, DM	NT	SU	117	(Jackson *et al*. 2007)

Bait uptake results



The first aim of the present study was to determine which species take baits deployed in areas inhabited by quokkas that have been intensively baited for 15–17 years for fox control. Baits were laid according to current management practice to control red foxes, and therefore our experimental design opportunistically followed available baits at these seven sites to record species uptake of these baits. Non-target uptake of baits will affect the bait density (initial number of baits available per area) and baiting intensity (initial number of baits available per target animal per area) which affects efficacy of fox baiting. A second aim was, therefore, to determine the persistence of baits in the environment.

Materials and methods

Study sites

This study was carried out over seven northern jarrah forest sites located south-east of Perth, south-west Western Australia. All sites are within State Forest, managed by the state government conservation organisation (DPaW). These sites are ground-baited monthly in and around the riparian zone, primarily to protect mainland quokka populations. Baits were laid according to current management practice, and therefore, our experimental design opportunistically followed available baits at these seven sites. For example, baiting routes are determined by the location of suitable vehicle-access tracks, and the baiting frequency and intensity were determined by DPaW management guidelines (Department of Conservation and Land Management 1996). Because we needed to be on site on the day that the baits were laid (to ensure that we monitored them from the time of deployment), logistical constraints also limited the number of sites that could be monitored.

Fox baits (Probait® salami-style kangaroo meat baits injected with 3.0 mg of 1080 poison; manufactured by DPaW, Harvey, WA, Australia) were deployed on the ground in and around the seven study sites at approximately monthly intervals over 9 months. Baits were deployed along unsealed tracks within the forest. Once deployed, baits were not collected but were replaced the following month. Spacing of monitored baits was kept consistent with the standard protocols (1 bait every 100 m of track for three Jarrahdale sites and 1 bait every 200 m for the two Dwellingup and two Collie sites; Table 2). Baits were placed on the ground as per standard DPaW operating procedures (Department of Conservation and Land Management 1996) and were not covered or tethered. The number of baits monitored at each site (Table 2) varied according to logistical constraints, coordinating with the regular baiting times, distances between sites and monitoring at multiple sites simultaneously.

Remote-camera monitoring of baits – species identification

In total, 299 deployed baits were monitored at each of the seven sites over 9 months (March–November 2011); 142 of these baits were monitored with cameras on an *ad hoc* basis (Table 2). We had no opportunity to monitor bait take by using less intensive methods (e.g. records of prints around bait stations) because of the soil type and logistical constraints regarding importing sand to these sites. The baits monitored were those deployed in close proximity to the densely vegetated stream zone where quokka populations were being live-trapped (Dundas 2013). Results have been pooled over the seven study sites.

Reconyx HC500 HyperFire™ Semi-Covert IR remote cameras (Reconyx, Holmen, WI, USA) were set to take five photos per trigger. Cameras were fixed to a tree trunk at a height of ~0.5 m. Baits were placed within the detection zone of the camera (~1.5 m in front; confirmed with test photos, camera instruction manual used to identify detection zones). Cameras were removed at the next bait check, if the bait had been removed, and, therefore, we have some photos of 'empty' bait stations that were also analysed for the activity index.

Over 30 000 images collected over 804 camera trap-nights were manually viewed as jpeg files in a simple image viewer program (Windows Live Photo Gallery, Windows 7 Edition, Microsoft Corporation, Redmond, WA, USA). Separate capture events were defined as groups of photos of animals of the same species (passing by the camera, as well as investigating, taking or consuming a bait) separated by at least 30 min. This analysis yielded 818 separate capture events. An index of activity for all species on camera was calculated as a percentage of this total activity for those species identified as taking baits. 'Bait take' was defined as an animal consuming part or all of a bait, or being captured on camera taking the bait out of the field of view of the camera. When a single bait was observed to be consumed by two or three individuals of the same or different species, each was classified as a separate bait take event; this occurred for 27 baits ($n = 57$ bait take events), resulting in the identification of 130 bait take events for 100 baits. Time since deployment was

Table 2. Monthly numbers of baits laid and monitored at seven study sites during the study

In total, 299 baits were monitored for persistence, of which, 142 (numbers shown in parentheses) were also monitored by camera in an attempt to identify the species that removed the bait. Bait densities were estimated from the linear distance of bait transects

Location	GPS coordinates	Approximate bait density (# baits km^{-2})	Month								
			Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.
Chandler	–32.29714, 116.13080	7.7					10	10 (5)	10 (8)	10 (10)	10 (10)
Gervasse	–33.35892, 115.92075	13.3	10	10 (1)	8 (2)	6 (2)				10 (9)	
Hadfield	–33.18022, 115.97687	14.8	10	10	10 (1)	5 (1)				10 (7)	
Kesners	–32.64657, 116.00842	12.2		9		10 (2)	10	10 (4)	9 (8)		
Rosella	–32.26823, 116.07853	7.7					10 (1)	10 (7)	10 (7)	10 (8)	10 (10)
Thirty-One Mile	–32.26552, 116.17334	7.7					10 (1)	10 (5)	10 (6)	10 (10)	10 (10)
Wild Pig	–32.56753, 116.05503	15.1		6		1 (1)			6 (6)		
No. of total baits monitored			20	35	18	22	40	40	45	50	30

calculated as the number of nights since the bait was deployed when it was taken. For those 27 baits with multiple bait take events, the final night the bait was removed was used in the calculation for the average nights after bait distribution.

Bait take was compared with the relative abundance of each species (the 'activity index' for each species) by Chi-squared analysis, where the actual numbers of baits taken by each species were compared against expected values calculated assuming the baits were taken in proportion to species relative abundance.

Persistence of baits (including non-camera monitoring)

Baits not monitored by cameras ($n = 157$) were repeatedly checked on an *ad hoc* basis (because of logistical constraints of distance). Baits were checked at least once every 48 h within the first week after deployment, and weekly thereafter (for those baits still present) and scored as present or absent. Persistence of baits was assessed as the minimum number of nights that a bait was known to be present in the environment (i.e. the time from deployment until the last time that the bait was observed). To determine whether the minimum number of nights a bait persisted following deployment differed by month, a median test followed by a Pearson's Chi-squared test was carried out (Statistica 8.0, StatSoft Incorporated, Tulsa, OK, USA).

The level of statistical significance was set at $\alpha = 0.05$ for all statistical tests.

Results

Positive identification of species uptake was recorded for 100 of the 142 baits monitored by camera; no photo evidence of the species taking the bait was recorded for 40 baits, and two baits were still present when rebaiting occurred 1 month later. Foxes accounted for only a single bait take (Fig. 1*a*). Quokkas accounted for the greatest number of non-target bait take events (48%, Fig. 1*a*) and 51% of bait takes occurring within the first two nights after deployment were attributed to quokkas (Fig. 2*a*). Other native species observed eating or taking baits at bait stations included brush-tailed possum, southern brown bandicoot, western grey kangaroo, *Macropus fuliginosus*, western brush wallaby, *Macropus irma*, chuditch, mardo, *Antechinus flavipes*, bobtail, *Tiliqua rugosa*, Australian magpie, *Cracticus tibicen*, and Australian raven, *Corvus coronoides*, whereas two introduced non-target species (feral pig, *Sus scrofa*, and black rat, *Rattus rattus*) took 4% of baits (Figs 1, 2*a*, 3*a–d*). Therefore, native species together accounted for 95% of the 130 bait take events, with all non-target species accounting for 99% of baits.

In total, 27 baits were eaten by more than one animal, including two individuals of the same species ($n = 8$ baits), three individuals of the same species ($n = 1$), two individuals of different species ($n = 16$), three individuals of different species ($n = 1$) and three individuals of two species ($n = 1$). All multiple bait takes were attributed to native species (quokkas, southern brown bandicoots, brush-tailed possums, western grey kangaroos, mardo, Australian magpie and Australian raven), except one bait take by a black rat. Animals did not show any obvious aversion to baits that had previously been nibbled by the same or different species (i.e. there were no indications of animals backing away from these baits or exhibiting hesitation in consuming baits).

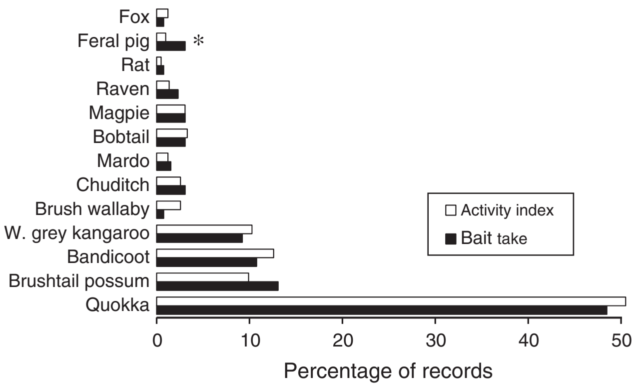


Fig. 1. Percentage of bait take events compared with the activity index of each species. Bait take events are the proportion of 130 bait take events (of 100 baits monitored) where species responsible for bait take could be positively identified. Activity index is the percentage of a total of 818 observations of individual animals over 804 camera trap-nights (photos from all monitored baits were pooled for a total of 818). 'Other' species that did not eat or take baits ($n = 38$ observations) have not been included in this chart. Asterisk indicates a significant difference (χ^2 analysis) between the number of bait take events and the number predicted from the species activity index at these sites.

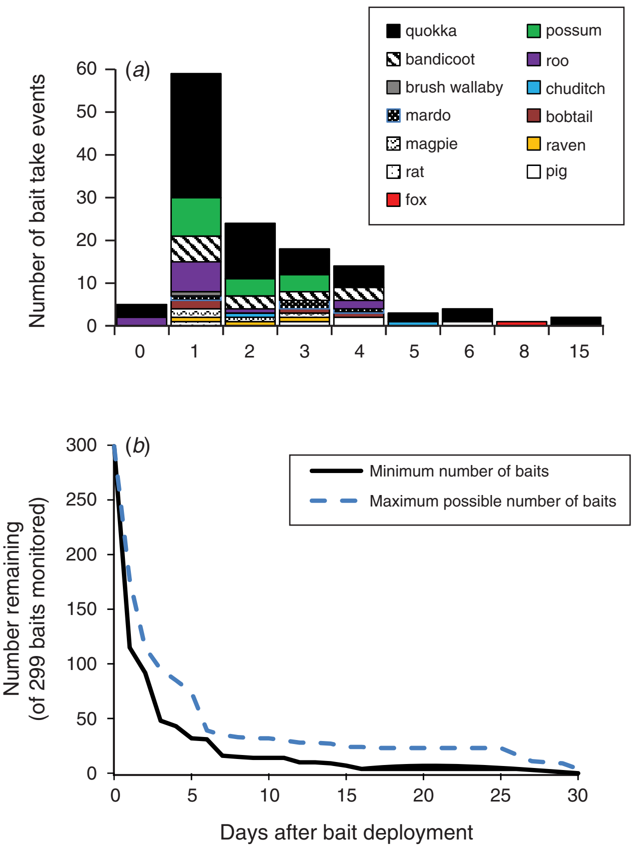


Fig. 2. Persistence of baits in the environment shown for (*a*) 130 bait take events (of 100 baits) where the species taking the bait was confirmed by camera, and (*b*) for the total of 299 baits (including those monitored daily for bait presence only).

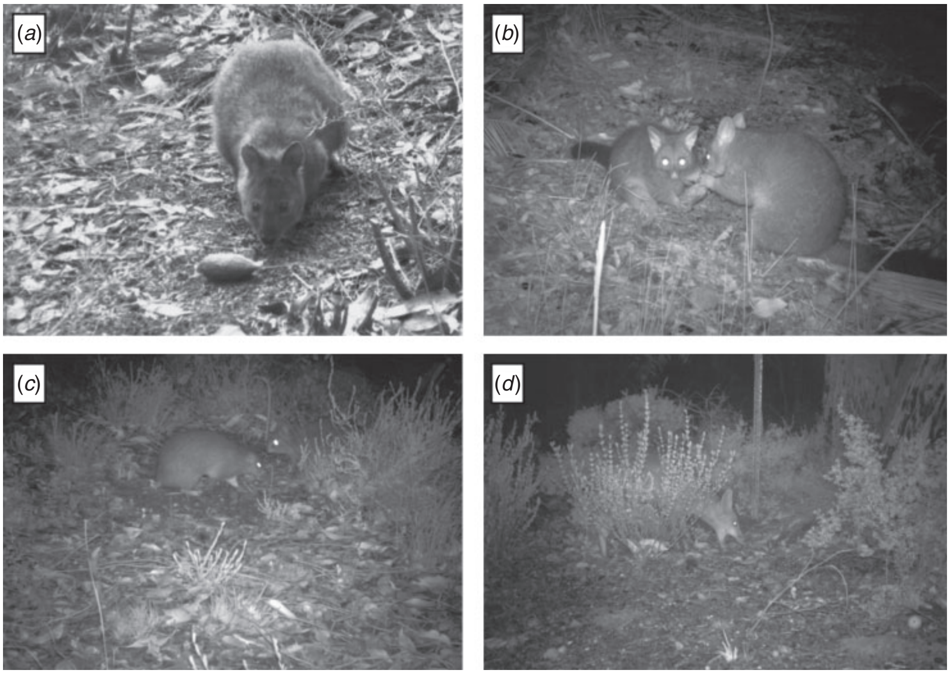


Fig. 3. Remote-camera photos showing species taking Probait® poison baits in the northern jarrah forest. (*a*) Quokkas accounted for a majority of bait uptake. (*b*) Brush-tailed possums took baits and there was evidence that young joeys were learning to take baits. Multiple species interacted over the baits; (*c*) shows a southern brown bandicoot (left) and quokka (right). (*d*) The only bait take by a fox was 8 days after deployment.

In total, 856 observations of species passing cameras across all sites were recorded, of which 818 were of species that were also observed taking baits. Overall, bait take by species was not significantly different from the activity of these species observed on camera (Fig. 1; $\chi^2_{12} = 10.98$, $P = 0.530$). When analysed by species, feral pigs were the only species that took baits more frequently than predicted on the basis of their activity indices (Fig. 1; $\chi^2_1 = 5.86$, $P = 0.016$); all the other species took baits in proportion to their activity index.

At least 69% of the 299 baits monitored were taken within two nights of deployment, with at least 62% being taken before (8 baits were observed on camera taken before the first night) or on the first night of deployment (Fig. 2*b*). At least 95% of baits were gone by Day 7, and only four baits were still present a month later, when the sites were re-baited. The minimum number of nights a bait remained out differed significantly among months of deployment ($\chi^2_8 = 29.55$, $P = 0.003$; Fig. 4). Baits deployed in winter (June–August) showed the fastest uptake, whereas baits laid in autumn (March–May) lasted for longer in the environment.

Only a single bait take by a fox was recorded, on Night 8 (1 of 10 fox records were a bait take) (Figs 2*a*, 3*d*). Red foxes were detected at three sites on camera at bait stations on Nights 1 ($n = 4$), 4 ($n = 2$), 5 ($n = 2$) and 8 ($n = 2$) after bait deployment. Additional observations of foxes over the long-term study at these sites (Dundas 2013) indicated fox presence at a fourth site, although foxes were not observed interacting with any bait stations at this site. On four occasions when foxes visited bait stations, the bait had already been removed. However, on five occasions foxes passed by while the bait was still present. Four

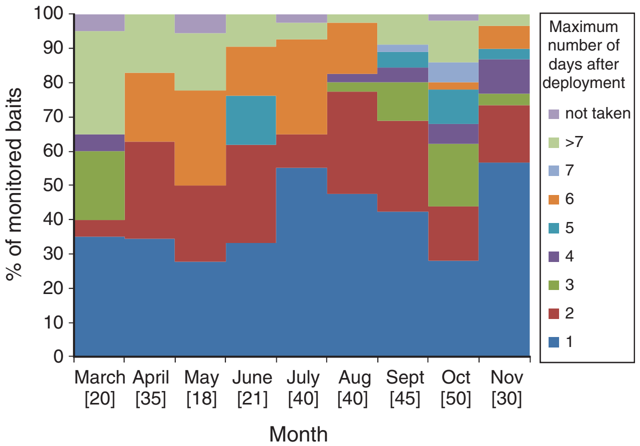


Fig. 4. Percentage of 299 baits monitored over 9 months, showing the minimum number of nights that baits were present after deployment. All sites have been pooled. Numbers in square brackets under each column are the total number of baits monitored.

observations included some interaction with the baits; foxes sniffed the bait or the place the bait had been; for the remaining five occasions, foxes walked past the bait station. One fox showed some wariness of the bait or camera (i.e. it approached the camera field of view from each side staring at the camera, but retreated, leaving the bait) and most foxes appeared to be aware of the glow of the IR camera flash or the sound of the camera operating (foxes were captured staring directly at the camera).

In addition to the 13 species seen taking and eating baits (Fig. 1*a*), eight other species were detected on camera, including feral cat, Gould's monitors, *Varanus gouldii*, short-beaked echidna, *Tachyglossus aculeatus*, common bronzewing pigeon, *Phaps chalcoptera*, red capped parrot, *Purpureicephalus spurius*, emu, *Dromaius novaehollandiae*, woylie, and European rabbit *Oryctolagus cuniculus*. Gould's monitors and feral cats interacted with baits but did not eat or remove them from the bait station.

Feral cats were observed at four of the seven sites (both foxes and cats were observed at two sites). One cat passed by a bait 2 h after it was deployed, but did not appear to interact with it. A second cat was captured on camera after the bait had been out for 4 nights and appeared to play with the bait for ~4 min before leaving it.

Discussion

The majority of baits were taken by non-target animals within a few nights of deployment, with species largely taking baits in proportion to their abundance at the seven study sites. Quokkas were the primary species taking baits, reflecting the focus of ground-baiting programs in areas with known quokka populations. The rapid uptake and large number of non-target species taking baits clearly decreases the likelihood of foxes encountering baits, thereby partly explaining the low uptake by foxes that we observed on camera and reducing the efficacy of the baiting program. We discuss these findings in regard to the risk to native fauna, and the efficacy of current baiting programs for the control of foxes.

Non-target bait uptake

The intensive monthly ground-baiting regime in the northern jarrah forest has been ongoing for 15–17 years (Hayward *et al.* 2003). This long-term exposure to baiting practices (vehicles passing through the area, the presence of the baits themselves) could result in resident native species becoming habituated to baits, contributing to the high rate of non-target uptake. Non-target animals taking baits is likely to continue because the baits are an easy and abundant source of protein, even for species recognised as being primarily herbivorous, such as the quokka.

Given the tolerance of Western Australian fauna species to 1080 poison, it is unlikely that any of the observed non-target species in the present study would have ingested a lethal dose (McIlroy 1982, 1983, 1984, 1986; Twigg and King 1991; Twigg *et al.* 2009), although this cannot be confirmed without searches post baiting; even then, the likelihood of finding potentially poisoned carcasses would be very low.

Quokkas were observed carrying baits out of the camera field of view, but they were also regularly seen eating them on camera. Mainland quokkas have a high tolerance to 1080, with an estimated median lethal dose (LD_{50}) of 40–60 mg·kg^{-1} (Mead *et al.* 1985). An average-sized adult quokka (3.38 ± 0.68 kg; Dundas 2013) would therefore need to consume between 36–80 baits containing 3 mg of 1080 within 12–24 h to receive a lethal dose (Mead *et al.* 1985). With the current baiting density in swamp systems being one bait per 100 m or 200 m of track, no adult quokkas are likely to be lethally poisoned from eating 1080 baits (quokkas would be required to move 3.6–16.0 km along tracks that had been baited in 12–24 h and consume all baits encountered to receive a lethal dose).

Despite a minimal risk for adult quokkas, there is a potential for poisoning quokka pouch young. Previous studies have shown that pouch young of tammar wallabies (*Macropus eugenii*), common brush-tailed possums and northern quolls (*Dasyurus hallucatus*) are more sensitive to 1080 than are adults (McIlroy 1981), with possum and quoll pouch young dying after ingesting a lethal dose of 1080 through their mother's milk, even though the female ingested a sublethal dose (McIlroy 1981). We observed female quokkas, brush-tailed possums and western grey kangaroos with pouch young eating baits, and large young-at-foot also readily consumed baits alongside their mothers (e.g. Fig. 3*b*), suggesting that bait consumption could be a learned behaviour. However, the quokka population at these sites was monitored for the previous 2 years and the number of pouch young present in the population (Dundas 2013) suggested that the potential effects of 1080 are not detrimental for these animals.

The chuditch was the only native species observed taking a bait that could potentially be affected by the dose of 1080 present. Chuditch have a LD_{50} of 7.1 mg·kg^{-1} (Twigg *et al.* 2009), so that a 1-kg animal could die after eating two or three baits, which is feasible when baits are closely deployed, as they are at these intensively baited sites (with a bait every 100–200 m). The bait densities of 7–15 per km^2 means that there would be multiple baits laid within the species home range (mean core area for females is 0.9 + 0.2 km^2 and over 4 km^2 for males, Serena and Soderquist 1989), although limited persistence in the environment would reduce the number that chuditch is likely to encounter. A previous bait take study found that 19 of 20 baits observed to be taken out of view of the camera by spotted tailed quolls (*Dasyurus maculatus*) were found uneaten a close distance away (Körtner *et al.* 2003). We did not find discarded baits during the current study, as sites were thoroughly searched when cameras were removed, and, on at least 40 occasions, non-target species were observed partially eating baits while they were still viewed on camera.

Persistence of fox baits and fox interactions with baits

The rapid and high level of bait uptake by non-target species observed in the present study clearly results in reduced bait availability for foxes. Bait take by foxes reflects relative bait availability and time to detection, because time to locate baits is a product of home-range utilisation by foxes in relation to bait placement and the availability of baits when the fox gets there. The only recorded bait take by a fox was after 8 days, when at least 95% of monitored baits had already been taken by non-target species.

No radio-tracking studies have been specifically conducted on foxes in the northern jarrah forest, but home-range estimates from other studies in a range of environments have suggested that foxes can cover large areas, with estimates of home range varying with habitat (e.g. semi-urban: 60–130 ha, Coman *et al.* 1991; coastal: 120–520 ha, Phillips and Catling 1991; 23–135 ha, Meek and Saunders 2000; semi urban riparian: 19–153 ha, White *et al.* 2006). Non-target species taking baits and behaviour of target species before foxes discover them reduces the intended bait availability at these intensively baited sites in the northern jarrah forest. The presence of large populations of non-target, 1080-tolerant species will therefore reduce bait presence for foxes. For example, lace monitors (*Varanus varius*) (which have a tolerance to 1080 of 119 mg kg^{-1} McIlroy *et al*. 1985) reduce the availability of baits for wild dogs in Victoria and the Northern Territory (Robley *et al*. 2009; Woodford *et al*. 2012).

The other issue made evident in the present study was that, even when the bait was present, foxes were likely to pass by without taking it. Foxes were detected on camera on 10 separate occasions. For four of these observations, baits had already been removed by non-target species. Only one fox took the bait on the six occasions when the bait was still present. The rate of bait uptake by target species can be influenced also by other factors, including habitat type (Trewhella *et al*. 1991; Carter and Luck 2013), season (Woodford *et al*. 2012), bait type (van Polanen Petel *et al*. 2001) and the availability of alternative food sources (Roberts *et al*. 2006; Moseby *et al*. 2011). Therefore, if foxes are likely to take only a small proportion of presented baits under most circumstances, the reduction in the number of baits available owing to non-target bait take becomes a significant problem.

Implications for management

The aim of any baiting regime is to reduce negative impacts by maximising the control of the target species (Saunders *et al*. 1995), while minimising any negative effects on non-target species (Glen *et al*. 2007). A baiting regime should be reassessed to improve efficacy when either control of the target is reduced or bait uptake by non-targets is suspected. In Western Australia, there has been a long history of fox control with initially promising results (Thomson *et al*. 2000; Burrows and Christensen 2002); however, major declines in monitored prey species within baited areas have been observed recently (Wayne *et al*. 2011, 2013). Similar observations in other long-term baited areas have raised the question of whether baiting is still effective (Walsh *et al*. 2012). The costs (both financial and in terms of time) of aerial baiting and targeted ground-baiting are sufficient to warrant monitoring the efficacy of these programs as well as the investigation of alternative deployment methods. In addition, there needs to be a greater emphasis on understanding the target species as well as interactions between predator and prey species.

Very little is known about the density, home range and diet of foxes in the northern jarrah forest. Fox numbers have not been monitored or quantified (not even relative activity indices) across the areas we were working. Without this critical information, effective control is challenging, and makes assessment of control efficacy and comparison among studies problematic, as discussed by Fleming (1997). Fox populations can differ vastly in their habitat use, given they inhabit a wide range of environments (e.g. urban, agricultural, forest, arid; Phillips and Catling 1991; Lucherini and Lovari 1996; Moseby *et al*. 2009*b*), all of which exert different selection pressures and influences on this invasive species. Information on the movements and habitat use of target species could be applied to improve efficacy of baiting regimes (Moseby *et al*. 2009*b*); for example, identifying whether the location of bait placement influences the chances of foxes locating and consuming the baits.

Populations of invasive species that have been exposed to control methods for a long period are likely to differ in their response to baiting, in comparison to a naïve population, because long-term exposure might select for bait-wary individuals. Even when control methods are sufficient to eliminate the majority of a free-ranging pest population (Marlow *et al*. 2000; Thomson *et al*. 2000), if they are not 100% effective, there is intense selection pressure driving future bait-avoidance behaviour. Aversion to 1080 baits has become an issue for control of brush-tailed possums in New Zealand where this poison has been used as a method of control for 57 years (Morgan *et al*. 1996). In New Zealand, O'Connor and Matthews (1999) recorded 60–80% of possums avoiding baits in areas that had previously been baited with 1080, compared with an avoidance rate of 0–20% for naïve possums, suggesting possums had been exposed to sublethal doses and learned avoidance. Bait avoidance in long-term intensively baited sites in Western Australia is an issue that has not been quantified, but may be of vital importance for effective control of foxes with 1080.

On the basis of our findings, there are three areas where further research could improve the current intensive ground-baiting regime in south-west Western Australia. First, there needs to be focus on reducing non-target bait uptake. Deterrents such as short-term bittering agents (e.g. Andelt *et al*. 1994; Woolhouse and Morgan 1995) may assist in discouraging resident native species, resulting in the prolonged persistence of baits within the environment (thereby increasing the chance of foxes encountering intact baits), although it would be important to ensure that foxes are not similarly exposed. Alternatively, the development of species-specific toxin-delivery techniques or devices could be considered (e.g. M44 ejectors, Marks *et al*. 1999; Scentinel®, King *et al*. 2007; Cat Assassin, Read 2010). Second, a better understanding of fox presence and landscape use in forested habitats would be beneficial. Regularly monitored sand pads are an effective means of monitoring predator and prey presence in a forested area (Claridge *et al*. 2010) and DNA genotyping of fox scats has successfully been used to estimate fox abundance and movements (Marks *et al*. 2009; Berry *et al*. 2012). Remote tracking with radio and GPS collars is a suitable method for determining habitat preferences and use of space (Lucherini and Lovari 1996; White *et al*. 2006), which could be used to improve bait deployment. Third, more information is required on how foxes interact with baits in these intensively baited sites and whether or not avoidance is an issue that is limiting bait uptake. In south-eastern Australia, GPS collars fitted to free-ranging wild dogs provided valuable details on the home range of wild dogs in relation to the presence of aerially distributed baits (Robley *et al*. 2009). Remote tracking of foxes could be carried out in areas where baits are deployed on ground and by air to determine fox home range in relation to baited areas. Baits could simultaneously be monitored with remote cameras to determine persistence within the areas being used by foxes. Monitoring baits with cameras is an effective method to establish time until bait take, species taking baits and behaviour of target species near baits, as has been shown in the present and other (Glen and Dickman 2003;

Hegglin *et al*. 2004; Takyu *et al*. 2013) studies. A better understanding of foxes and their responses to prescribed control methods will assist with the development of more targeted and efficacious baiting regimes in the future.

In conclusion, the sites that we monitored have been baited monthly over the past 15–17 years for the control of fox numbers and protection of known quokka populations. However, as a consequence of the large numbers of native animals present, 99% of 1080 baits were taken by non-target species, reducing availability to the targeted foxes. The high bait density at these sites, therefore, does not directly equate to an equivalent high baiting efficiency because of excessive levels of non-target interference, resulting in a low proportion of baits surviving past 1 week. The reduced availability of baits to foxes has the potential to reduce the effectiveness of the program over time, which warrants further investigation.

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