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Detectability of sodium fluoroacetate (1080) in wild dog baits and impacts on bait uptake

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ABSTRACT

Context. Wild dog impacts on agricultural and environmental systems in Australia are commonly managed through broadscale baiting using sodium fluoroacetate (1080). There has been growing evidence of bait avoidance in some populations of wild dogs throughout Australia, raising concerns about the efficacy of 1080 baiting. Bait avoidance can be a learned behaviour in a population, which could be caused by several factors associated with baiting programmes. One potential causative factor in developing bait avoidance is the ability to detect and respond to the toxin in the bait. The toxin 1080 is described as odourless and colourless to dogs, suggesting limited cues for its detection, but has not been formally tested. **Aims.** This study used a trained detector dog to evaluate the detectability of 1080 to a dog and then the detectability in a variety of bait matrices. We also used a field trial to assess if 1080 dried meat baits were less likely to be taken than non-toxic baits in sites with a history of dog baiting or no dog baiting. **Methods.** We trained a detector dog to detect 1080 odour and trialled this ability on different bait matrices. We used a field-based cafeteria-style trial to investigate the possibility of toxin detection by wild dogs. **Key results.** We demonstrated that a trained dog could detect the presence of 1080, but detectability of the toxin when presented in different baits was variable and mostly greatly reduced. The field trials demonstrated no significant difference in bait take between 1080 and non-toxic baits by wild dogs in either a bait-naïve or bait-exposed population. **Conclusions.** These results suggest that, while 1080 is potentially detectable, factors other than its presence are responsible for bait avoidance in wild dog populations. **Implications.** Wild dog management is heavily reliant on baiting with 1080 to reduce populations and thus reduce impacts on the environment and agriculture. The use of 1080 is unlikely to be the cause of bait avoidance and so where reduced uptake of baits by dogs is occurring, other factors need to be investigated and addressed.

Keywords: Bait resistance, baiting, detector dog, dingo, learned aversion, toxin, vertebrate pest management, wild dog control.

Introduction

Wild dogs (dingoes, free-roaming domestic dogs and their hybrids; *Canis familiaris*) cause millions of dollars of loss to sheep, goat and cattle production in Australia every year (McLeod 2016). Despite on-going population control, they remain a significant problem for livestock producers across many pastoral and agricultural regions of Australia (reviewed by Fleming *et al.* 2014). Effective control of wild dog populations is therefore a priority for affected livestock producers. Wild dogs also prey on a wide variety of native fauna in Australia and are a known or potential threat to at least 14 endangered or vulnerable native animals (National Wild Dog Action Plan 2020; Fleming *et al.* 2022). For example, in south-east Queensland wild dog predation is a significant cause of mortality in koala populations (Beyer *et al.* 2018; Gentle *et al.* 2019) and intensive management programmes to remove wild dogs can assist to reverse population declines (Beyer *et al.* 2018). Wild dogs are also known to prey on large native mammals (e.g. macropods and wombats), critical

weight range mammals (e.g. echidna, possums, bettongs and bandicoots), small mammals, reptiles and birds (reviewed by Doherty *et al.* 2019; Fleming *et al.* 2022). They are also carriers of zoonotic pathogens and parasites that can impact native animals and livestock (Harriott *et al* 2019). The impacts of wild dogs on native species and human activity drive continued research on effective control measures for wild dog populations.

Coordinated baiting is the most cost-efficient form of landscape-scale wild dog population control (Fleming *et al.* 2014). However, there is evidence of bait resistance (*sensu* Allsop *et al.* 2017) in some wild dog populations, which could be due to the strong selection pressure for neophobic animals that avoid baits, coupled with learned aversion in animals that have been exposed to sub-lethal baits (Allsop *et al.* 2017). In the southern rangelands of Western Australia, Kreplins *et al.* (2018) reported that only four of 337 dried meat baits of known fate were taken by wild dogs (i.e. 1.2% bait-take by wild dogs). All bait takes were by young dogs, i.e. likely bait-naïve animals. Furthermore, of the 1809 wild dog activity events on camera, 18% of those also had a bait in the image, indicating that wild dogs were encountering baits at a much higher rate than removal of baits. The dogs also showed potential aversive behaviour (pawing the bait and urinating or defaecating on the bait), indicating a potentially learned bait-avoidance in that population (Kreplins *et al.* 2018). Furthermore, there has been no population reduction in response to baiting for some study sites, suggesting limited uptake or consumption of baits (Kennedy *et al.* 2021).

A further issue in wild dog baiting programmes is the removal of baits by non-target animals. For example, Kreplins *et al.* (2018) reported that the majority of baits were removed by varanids and corvids. Similar results have been seen in wild dog baiting campaigns, with foxes and birds removing most baits (McIlroy *et al.* 1986), and in non-toxic studies of bait uptake, with birds (Allen *et al.* 1989) or native mice (Mason *et al.* 2025) removing more baits than wild dogs. The removal of baits by non-target animals impacts the efficacy of baiting programmes by reducing the potential encounter rate by the target species to the baits (e.g. Dundas *et al.* 2014; Kreplins *et al.* 2018; Hohnen *et al.* 2020). It also provides a direct risk to the individual animals consuming the bait. Studies have shown spotted-tailed quolls (*Dasyurus maculatus*) do consume and can die from wild dog baits (Körtner and Watson 2005; Cremasco and Selles 2008). The mortality rates, however, are much lower than expected from bait encounter rates and the impact to quoll populations is negligible compared to background mortality and the benefits of predator removal (Körtner and Watson 2005; Glen *et al.* 2007; Cremasco and Selles 2008). Strategic baiting practices should be considered to reduce bait uptake by non-target species to prevent negative impacts on those animals and to retain baits in the environment for the target species.

Traditionally, wild dog baits contain the toxin sodium fluoroacetate (compound-1080, hereafter 1080), which is often mixed with a coloured dye for human safety and to reduce non-target uptake. Although 1080 is often described as a colourless and odourless substance (e.g. PestSmart 2020), dogs may be able to detect it and so it might be a cue for rejecting a bait. To examine the detectability of 1080 in baits, a detector dog was trained to indicate on 1080 odour under controlled situations and then tested against different fresh and commercial wild dog 1080 baits. Detector dogs can be trained to specific target odours including animals such as feral cats (McGregor *et al.* 2016) and koalas (Kent and Cristescu 2020), diseases in humans (reviewed in Salgirli Demirbaş *et al.* 2021) or, as in this case, chemical residues such as explosive material and illicit substances (Lorenzo *et al.* 2003). The use of such a dog provides an opportunity to test whether it is possible for a dog to detect 1080 in isolation or in a bait. We also conducted field-based cafeteria trials at one site with a bait-naïve wild dog population and one site that was previously bait-exposed ('bait resistant', *sensu* Allsop *et al.* 2017). The aim of these field trials was to investigate whether wild dogs with previous exposure to 1080 baits would avoid the baits.

Materials and methods

Study 1. Detector dog trials

Training

A male springer spaniel was chosen to be trained in the detection of 1080. Standard industry training techniques of positive reward reinforcement (ball play) were used by a professional detection dog trainer (CAM) to teach the dog to discriminate the target odour (1080) from other odours and distractions. The training period included basic command recognition and behaviour requirements for indicating; that is, investigating a series of containers or objects with different odours and then holding position with the nose over but not touching any object he thinks has the target odour.

To reduce risk of accidental consumption of 1080, 0.2 mL of 1080 stock solution (Animal Control Technologies Australia – hereafter ACTA), was soaked onto filter paper (Qualitative, Medium Filtration, Low Ash, 47 mm diameter) and then evaporated off. This volume resulted in 6 mg of 1080 remaining present on the filter after the evaporation process and for up to 3 weeks post preparation (Supplementary data Table 1). Target odour filter papers were presented to the dog in stainless-steel pots with a mesh lid to allow odour to escape but prevent access to the filter papers. To allow testing of detection success, the dog was trained to search on scent walls, scent wheels and scent racks (Fig. 1 and Supplementary data Fig. S1). The use of these devices varied throughout the trials as the methodology using a toxic solution required novel equipment and new training processes for the dog. The use of multiple devices also allowed for

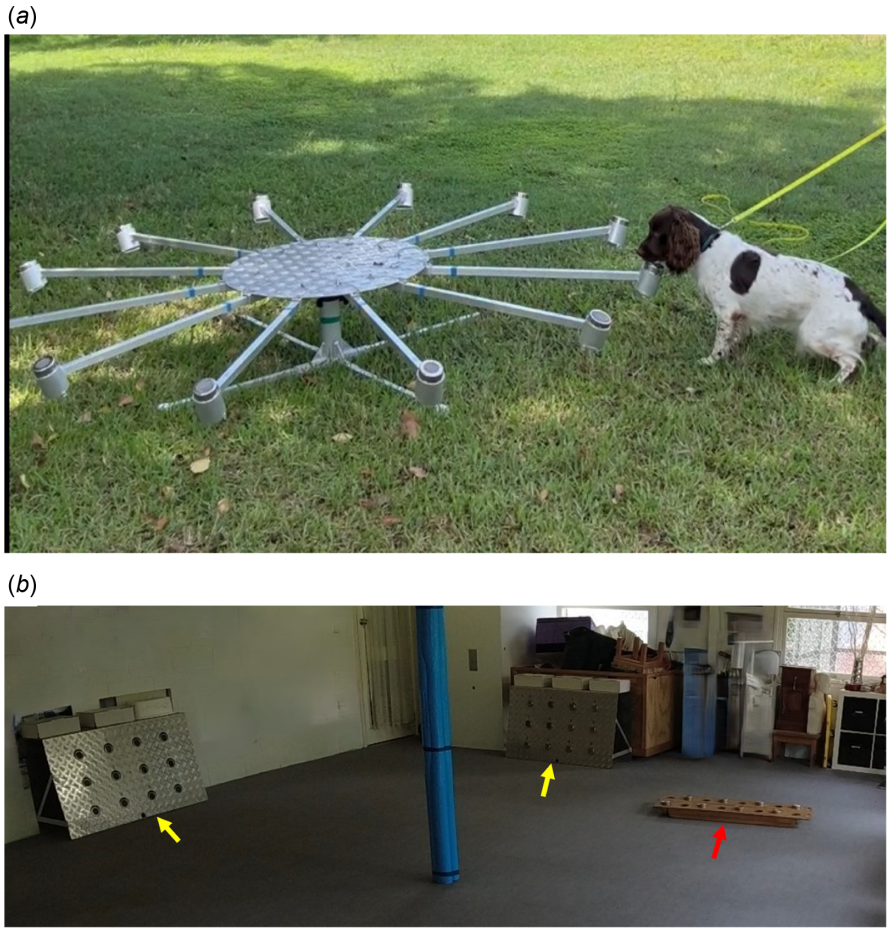

Fig. 1. (*a*) A scent wheel with the dog indicating on a pot, and (*b*) an example of a typical setup of two scent walls (yellow arrows) and an eight-pot rack (red arrow) allowing two or three trials to be run in succession. Photographs by Peter Elsworth.

additional randomness in odour location and other cues, removing potential accidental operator bias.

The dog was trained to search the scent device and indicate on the pot containing the target odour by standing still and looking at the pot. For scent wheels, the dog would start at a random position on the wheel and work counterclockwise around it. It was not required to inspect every pot but could indicate at any time it thought it had found the target odour. For the scent walls and racks, the dog would be directed to search the device and had free choice of start position and search pattern. The dog would indicate on the pot it thought had the target odour and again there was no requirement for all pots to be searched, although often they were. The trainer incorporated distractions into the training, such as human-contaminated gloves and cloths, toys and pulling on the lead and pushing the dog, so the dog understood to hold its indication on the pot without any cues from the handler. This allowed for unmistakeable identification of the indicated pot. All pots were washed in a dishwasher a minimum of three times between trials to avoid residual odour.

Trials

Following the training period, a series of trials were conducted to establish if the dog could detect 1080 (the target odour): (1) on the filter papers and then (2) in different wild dog bait matrices. To avoid the potential for unconscious bias, the handler and the dog were not present during preparation of the testing devices and all pots were handled during preparation to provide human scent on all equipment. Scent walls and racks were in an indoor training room and the scent wheels were located outdoors in a shaded area. For all trials, pots were numbered so an external observer could indicate to the handler if the correct pot was identified, to allow immediate reward (ball play) for the dog, when required. All tests were video recorded to allow inspection of search patterns and time to indication. The search pattern was the sequence of pots investigated by the dog and was used to determine if all pots containing treatments were investigated. Time to indication was calculated from the moment the trainer sent the dog to search to the time the trainer was satisfied the dog had indicated and called the pot number indicated on.

Imprinting trial

To examine whether the dog could detect the 1080 stock solution on filter paper, 20 tests were performed using the scent walls (n = 12) and scent wheels (n = 8). As the 1080 stock solution contains water and a blue dye (which could not be separated from the 1080 in the commercial product available), tests were run with each device having one pot containing:

1. Target treatment – a filter paper containing 1080 stock solution (1080 + blue dye + water) at 0.2 mL and evaporated off,
2. Non-target dye-only treatment – a filter paper with non-toxic solution containing blue dye + water provided by the manufacturer (ACTA) at 0.2 mL and evaporated off, and
3. Non-target treatment – a filter paper with distilled water at 0.2 mL and evaporated off.

The remaining pots were empty. Placement of the filter papers on the scent wall or wheel was chosen randomly, but if it resulted in treatments in adjacent pots, then a new pot number was randomly generated. We chose to have the filter papers in non-adjacent pots to reduce the risk of odour-spill confounding results at this early stage of testing. The order of devices used in each set of tests was also random. As two scent walls and two scent wheels were available, the dog was put through four tests and then rested for at least 15 min before the next four tests.

Discerning trial

Following the completion of the imprinting trial, it was determined that the dog required further training to discriminate between filter papers with the 1080 stock solution (target treatment) and filter papers with the non-toxic, blue dye solution (non-target dye-only treatment). After the training period, test runs were performed using scent wheels (n = 4), scent walls (n = 1), six-pot scent racks (n = 4) and eight-pot scent racks (n = 4) in random order. For each device, all pots contained a filter paper with only one randomly selected pot containing a 1080 stock solution filter paper (target treatment) and all remaining pots containing blue dye solution filter papers (non-target dye-only treatments). By placing a filter paper in every pot, the dog was required to make a decision on each pot whether the 1080 was present or not, allowing demonstration that he recognised that the filter paper, the blue dye and the water were not the target odour. The dog was put through one to two tests at a time and then rested for at least 30 min before the next tests.

Bait trials

Once it was established that the dog could discern the 1080 odour from the blue dye odour, tests were conducted to determine if 1080 odour was detectable in different bait matrices rather than just on filter paper. As part of the training process, the dog had been taught that foodstuffs (the dog's regular dry food pellets and fresh kangaroo meat) were a distraction and would not be rewarded if indicated on. The dog was also trained that a foodstuff in a pot with a 1080 stock solution filter paper was still the target odour and was rewarded if indicated on. This was an important step in the process so that the dog understood that even if something else was in the pot with the odour then it should still indicate that it had found the odour. As the baits being tested included the commercial wild dog baits DOGGONE® (ACTA) and 1080 Dried Meat Wild Dog Baits (ACTA), non-toxic samples of these were included in the training.

Four baits were tested against their own placebo baits:

1. Fresh kangaroo meat (~125 g) injected with 0.2 mL 1080 stock solution (ACTA) (resulting in 6 mg of 1080) vs fresh kangaroo meat (~125 g) injected with 0.2 mL non-toxic, blue dye only solution (ACTA) vs fresh kangaroo meat (~125 g) injected with 0.2 mL water,
2. 1080 DOGGONE® (ACTA) ~60 g, containing nominal dose of 6 mg of 1080 vs non-toxic DOGGONE® (ACTA), ~60 g,
3. 1080 Dried Meat Wild Dog Baits (ACTA), ~125 g, containing nominal dose of 6 mg of 1080 vs non-toxic dried meat wild dog baits (ACTA), ~125 g,
4. 1080 Canid Pest Ejector (CPE) wild dog capsules (ACTA), containing nominal dose 6 mg of 1080 vs non-toxic CPE capsules (ACTA).

The CPE wild dog capsules and non-toxic CPE capsules were kept intact and placed into pots without any other substance (i.e. no lures or CPE materials such as stakes or bait heads were included). Trials were performed using scent walls (n = 21) and eight-pot scent racks (n = 5) in an indoor training room. Indoor scent walls and racks were considered to be better suited for the dog to discern odour as it allowed the dog immediate access to all of the pots for investigation during self-directed searching for scent while also reducing the opportunity for potential scent drift. For the fresh meat bait trials, a single pot contained one bait with 1080 stock solution, two pots contained baits with non-toxic, blue dye only baits (one bait per pot), three pots contained baits with water only (one bait per pot) and the remaining pots were empty. For the other three bait-types, a single pot contained one 1080 bait, five pots contained the non-toxic baits (one bait per pot) and the remaining pots were empty. The placement of baits and order of bait-type were randomly assigned per device, as was the order of devices used in each set of tests. The dog performed two or three tests and was then rested for at least 15 min before the next tests.

Study 2. Non-toxic and toxic bait field trials

Study sites

This study was conducted at two sites (across three pastoral properties) in the southern rangelands of Western Australia.

Our first site in the Mid West Region was considered a 'bait-naïve' site. This property is currently an operational cattle station and had no wild dog control over at least the ~8 years prior to this study. The climate for this site typified an arid environment (mean annual rainfall 234 mm, 90% CI 65–483 mm) with a pattern of more irregular summer (cyclonic) rainfall (Fig. 2*a*). The vegetation was composed of *Acacia* spp. woodlands.

Our second site, 400 km away from the bait-naïve site, was considered a 'bait-exposed' site. This site covered two adjacent properties in the Murchison Region that had previously been used for sheep production although only unmanaged cattle and goats grazed the properties during the study. Both properties had a long history (~40 years) of 1080-baiting for wild dogs coordinated by the Meekatharra Regional Biosecurity Association (MRBA). In 2017/18, landholders within the MRBA deployed ~1.6 million baits across pastoral and conservation properties. The MRBA had exclusively used kangaroo meat up until about 6 years prior to this study, followed by 1 year with camel meat and then the most recent 5 years with horse meat. We have previously demonstrated low bait-take for two other properties within 70 km of this study site (Kreplins *et al.* 2018). For the present study, these two properties are considered together as the 'bait-exposed' site. The average annual temperature for this site averaged 3°C cooler than the

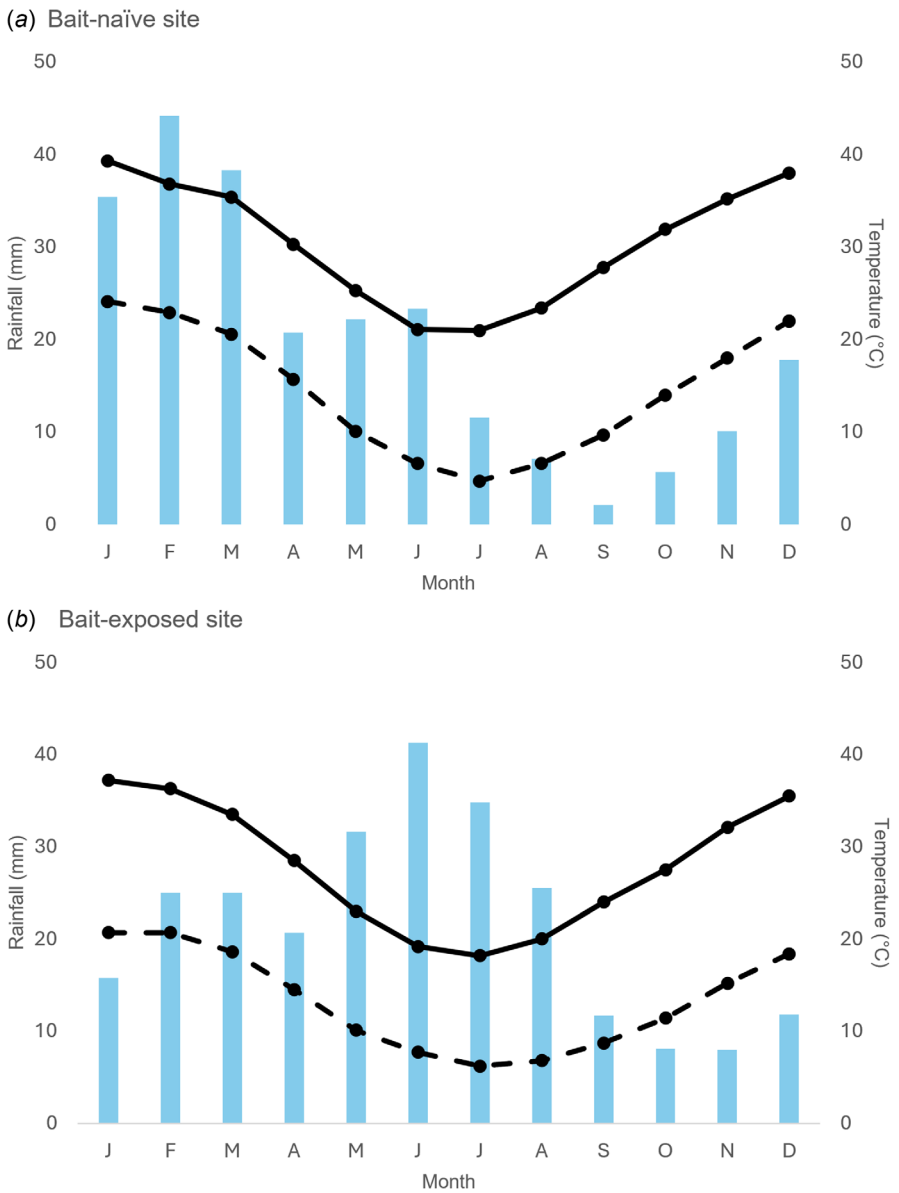

Fig. 2. Mean monthly rainfall and minimum (dashed line) and maximum (solid line) temperatures for the two study sites. Data reported are the annual averages recorded (Bureau of Meteorology 2017) for the nearest weather recording station to each site (*a*) BOM 007080, during 1967–2004, and (*b*) BOM 007091, during 1897–2014.

bait-naïve site and typified a semi-arid environment (mean annual rainfall 258 mm 90% CI 138–418 mm) with a more Mediterranean pattern of principally winter rainfall (Fig. 2*b*). The vegetation was similarly composed of *Acacia* spp. woodlands.

Experimental design

For each site, 45 camera traps (Reconyx Hyperfire 2 HP2X) were deployed approximately 1 km apart along property access roads (each field trip involved ~2500 km of travel); these formed our 'bait stations' for monitoring. The roads were graded, well-travelled gravel roads, generally wide enough for at least one vehicle to travel along. Cameras were mounted 0.3–0.5 m above the ground and directed at an angle of approximately 22.5° downwards facing along the track (Meek *et al.* 2012). Cameras were programmed to take a series of three photos in quick succession (rapidfire setting). Additionally, each camera trap was also programmed on time-lapse to take a single photo every 30 min as an attempt to capture activity of reptiles at the bait stations and to improve the determination of the species responsible for bait take. Animals captured on cameras were identified to species level where possible, with images tagged using ExifPro 2.1. Metadata for camera trap images were downloaded to a .csv database and the number of independent capture events was calculated, using a threshold of 10 min in 'camtrapR' (Niedballa *et al.* 2016). Thus, if a camera trap captured multiple images of wild dogs within a 10-min period, this was treated as one independent event unless there were multiple individual wild dogs in the photo. Camera detections of wild dogs were identified to individual wherever possible by a single observer (PAF), based on unique pelage markings.

Toxic (with 1080) and non-toxic versions of the same dried meat baits were manufactured at the same time by air drying ~100 g of fresh kangaroo muscle pieces on outdoor bait drying racks. Toxic baits were injected with 6 mg of 1080 as the muscle started to dry out (Thomson *et al.* 2006). Once baits were dried (each ~40 g), they were deployed in a cafeteria-style choice design (*sensu* Meier *et al.* 2012) by placing one non-toxic and one toxic bait on cleared ground approximately 5 m in front of a camera trap. Non-toxic and toxic baits were placed adjacent to each other approximately 0.5 m apart, perpendicular to the line of travel along the track to ensure an equal likelihood of initial encounter. At each camera, the non-toxic baits were on the left and toxic baits on the right of the image when photos are reviewed on a computer. Cameras were serviced every ~6 weeks and baits were replaced so that two fresh baits were in front of each camera. This occurred on four occasions during May–December 2020, resulting in a total of five bait pairs in front of each camera over the duration of the trail.

Statistical analysis

Study 1 – detector dog trials

As the expected frequencies were low, we used Fisher's exact tests, with expected values assuming an equal proportion of choices, to compare choice of filter paper or bait indication (Kim 2017), in the 'exact2x2' package (https://CRAN.R-project.org/package=exact2x2, Fay 2010). Pairwise Fisher's exact analysis in the 'rstatix' package (https://CRAN.R-project.org/package=rstatix, Kassambara 2023) were then used to determine significant associations between bait types and filter papers and phi (f) or Cramers v (V) confidence limits for effect sizes were determined using the 'statpsych' package (https://CRAN.R-project.org/package=statpsych, Bonett 2024). Search times between groups were compared using unpaired t-tests, with two-tailed distribution assuming equal variance.

Study 2 – non-toxic and toxic bait field trials

We used the Cox proportional hazards model to perform bait longevity (survival) analysis in the 'survival' package (https://CRAN.R-project.org/package=survival, Allignol and Latouche 2021), with time between deployment and bait-take for each bait tested against site. As there was no replication at the site level, formal testing between sites was not possible. We compared the fate of toxic and non-toxic baits using a Pearson's chi square test, with expected values assuming an equal proportion of toxic and non-toxic baits were removed.

All values are presented as the means ± standard error (s.e.) [range]. All statistical analyses were conducted in R (R Development Core Team 2010).

Ethical approval

All trials were undertaken within the scope of the Australian code for the care and use of animals for scientific purposes (8th Edition), 2013. Detector dog trials were undertaken under Department of Agriculture and Fisheries Community Access Animal Ethics Committee approval (CA2023/10/1788). Field trials were conducted under Murdoch University animal ethics approval (RW3189/19).

Results

Study 1. Detector dog trials

Imprinting trial

The dog indicated on the 1080 stock solution filter paper on nine of the 20 occasions, and the non-toxic, blue dye-only filter papers on nine occasions (Table 1, Supplementary material Table S2). The 1080 filter papers and blue dye-only filter papers combined were indicated significantly more than the blank filter papers, $\chi^2_{2,N=60} = 7.35$, $P = 0.025$. The remaining two tests resulted in indication on a blank filter paper and an empty pot. The indication on the empty pot occurred without the pots containing 1080 or blue dye-only filter papers being searched by the dog. When the blank filter paper was indicated on, all the pots had been examined.

The average search time across all tests was 8.9 ± 1.4 [1–27] s. When the 1080 filter paper was indicated the

Table 1. Outcomes of the imprinting trial.

Treatments (number offered in each test run)	Number of times indicated		Average search time ± s.e. (s)
	Out of number of trials	Out of total times offered	
Filter paper with 1080, blue dye, water (n = 1)	9 of 20	9 of 20	10.44 ± 2.88
(C1) Filter paper with blue dye, water (n = 1)	9 of 20	9 of 20	7.44 ± 1.76
(C2) Filter paper with water (n = 1)	1 of 20	1 of 20	3[A]
(C3) Empty (n = 9)	1 of 20	1 of 180	4[A]

Each test run contained one target treatment (containing 1080), and three control treatments (C1–C3). A scent wall (n = 12) or wheel (n = 8) was used for a total of 20 test runs, with 12 pots used for each run. The number of times each treatment was indicated is shown for those 20 test runs (number of trials), and for the total number that each treatment was available to the dog across all the test runs (total times offered). The average search time is the time from the dog being sent to investigate to indication.

[A]Only indicated on one occasion so value is the time for that instance only.

Table 2. Outcomes of the discerning trial.

Treatments (number offered in each test run)	Number of times indicated		Average search time ± s.e. (s)
	Out of number of trials	Out of total times offered	
Filter paper with 1080, blue dye, water (n = 1)	13 of 13	13 of 13	4.77 ± 0.85
(C1) Filter paper with blue dye, water[A]	0 of 13	0 of 103	NA

Each test run contained one target treatment (containing 1080), and one control treatment (C1). A scent wall (n = 1), scent wheel (n = 4), six-pot rack (n = 4) and eight-pot rack (n = 4) were used for a total of 13 test runs. The number of times indicated is shown for those 13 test runs, and for the total number that each treatment was available to the dog across all the test runs (total times offered). The average search time is the time from the dog being sent to investigate to indication.

[A]Number of controls varied according to the testing device used: wheel (n = 11), six-pot rack (n = 5), eight-pot rack (n = 7) and wall (n = 11).

average search time was 10.4 ± 2.9 [1–27] s and when the dye-only filter paper was chosen the average search time was 7.4 ± 1.8 [1–18] s. There was no significant difference between these search times (P = 0.356). There was also no significant difference in search time (P = 0.882) for type of device between scent walls (9.1 ± 2.0 s) and scent wheels (8.6 ± 2.0 s). As there was no difference between the proportion of indications or search time on filter papers containing 1080 or filter papers containing only the blue dye, the results suggest that the dog was indicating on the blue dye odour rather than the 1080 odour.

Discerning trial

Following additional training to discern the 1080 from the blue dye the dog indicated on the 1080 stock solution filter papers in all 13 tests (Table 2, Supplementary material Table S3). On 12 occasions, indication was on the target treatment pot on the first encounter with the pot. In all tests, at least one non-target treatment pot was examined before indication on the 1080 pot. The average search time was 4.8 ± 0.9 [1–13] s. There was no significant difference (P = 0.380) between the scent wheels (5.8 ± 1.8 s) and scent racks (4.1 ± 0.7 s). This clearly demonstrates that the dog was able to discriminate the 1080 odour from the dye. The search times in the discerning trial were significantly quicker (P = 0.046) than the imprinting trial when the dog indicated on a 1080 or dye-only filter paper (8.9 ± 1.5 [1–27] s), indicating improved search behaviour and more certainty in detecting the target odour.

Bait trial

Detection of 1080 among the baits was variable and significantly different (P < 0.001). DOGGONE baits containing 1080 were more likely to be indicated than the fresh meat (f = 0.750, 95% CI 0.62–0.84, P = 0.020), dried meat (f = 0.854, 95% CI 0.738–0.921, P = 0.014) or CPE capsules (f = 0.854, 95% CI 0.738–0.921, P = 0.014) (Table 3, Supplementary material Table S4). DOGGONE baits containing 1080 were correctly indicated on seven of the eight tests. On the one incorrect indication, the dog indicated on an empty pot. Fresh meat baits containing 1080 were indicated on one of the eight tests. One indication was on fresh meat injected with water only, and for the remaining six occasions an empty pot was indicated. Dried meat baits containing 1080 were indicated on zero of the five tests, with two indications on a non-toxic bait and the remaining three on empty pots. The CPE capsules containing 1080 were also indicated on zero of the five tests, with one indication on a non-toxic CPE capsule and the remaining four on empty pots.

Search time was generally the least for DOGGONE baits (14.3 ± 3.5 [8–36] s), followed by dried meat baits (15.6 ± 2.1 [10–24] s), CPE capsules (19.0 ± 2.5 [12–26] s) and with fresh meat baits taking the longest (24.0 ± 4.1 [9–41] s). As only one fresh meat bait with 1080 was indicated on, and no 1080 baits for dried meat and CPE capsules, comparisons of time to detection when 1080 was chosen could not be made. There was no significant difference in the search times for each bait type, ANOVA, $F_{3,20}$ = 1.48, P = 0.249. The search time for all bait tests (18.4 ± 1.9 [8–41] s) was significantly longer than for all filter paper (imprinting and discerning trials combined) trials (7.2 ± 1.0 [1–27] s) (P < 0.001). Search times were also significantly longer when 1080 in baits was indicated (14.9 ± 3.4 [8–36] s) compared to filter papers (imprinting and discerning trials combined) when 1080 was indicated (7.1 ± 1.3 [1–27] s) (P = 0.019). Detection of 1080 was more likely on filter paper (from the discerning trial) than in baits (V = 0.905, 95% CI 0.750–0.972, P < 0.001), with the exception of DOGGONE (f = 0.285, 95% CI 0.187–0.378, P = 0.544).

Table 3. Outcomes of the bait trial.

Matrix. Number of tests: devices used (number of times)	Treatments (number offered in each test run)	Number of times indicated		Average search time ± s.e. (s)
		Out of number of trials	Out of total times offered	
Fresh meat. 8 test runs: 8-pot rack (2), wall (6)	Fresh meat with 1080, blue dye, water (n = 1)	1 of 8	1 of 8	13[A]
	(C1) Fresh meat with blue dye, water (n = 2)	0 of 8	0 of 16	NA
	(C2) Fresh meat with water (n = 3)	1 of 8	1 of 24	34[A]
	(C3) Empty[B]	6 of 8	6 of 40	24.20 ± 4.98
DOGGONE. 8 test runs: 8-pot rack (2), wall (6)	1080 DOGGONE (n = 1)	7 of 8	7 of 8	15.17 ± 3.96
	(C1) Non-toxic DOGGONE (n = 5)	0 of 8	0 of 40	NA
	(C2) Empty[B]	1 of 8	1 of 40	9[A]
CPE capsule. 5 test runs: 8-pot rack (1), wall (4)	1080 CPE toxic capsule (n = 1)	0 of 5	0 of 5	NA
	(C1) CPE non-toxic capsule (n = 5)	1 of 5	1 of 25	13[A]
	(C2) Empty[B]	4 of 5	4 of 26	20.50 ± 2.59
Dried meat. 5 test runs: wall (5)	1080 dried meat wild dog bait (n = 1)	0 of 5	0 of 5	NA
	(C1) Non-toxic dried meat wild dog bait (n = 5)	2 of 5	2 of 25	19.00 ± 3.54
	(C2) Empty (n = 6)	3 of 5	3 of 30	13.33 ± 1.66

Each test run contained one target treatment (containing 1080), and two or three control treatments (C1–C2 or C1–C3). A scent wall or eight-pot rack was used for the test runs. The number of times indicated is shown for those test runs (number of trials), and for the total number that each treatment was available to the dog across all the test runs (total times offered). The average search time is the time from the dog being sent to investigate to indication.

[A]Only indicated on one occasion so value is the time for that instance only.

[B]Number of controls varied according to the testing device used: eight-pot rack (n = 2) and wall (n = 6).

Study 2. Non-toxic and toxic bait trials

We recorded a total of 3306 photos of wild dogs, with 98% of images able to be ascribed to an individual based on age estimation, unique pelage markings or body shape. These photos represented 267 independent wild dog detections (177 detections of 52 individuals at the bait-naïve site and 90 detections of 32 individuals at the bait-exposed site). For 47 wild dogs that were seen on more than one occasion and the distance between consecutive sightings could be calculated, they were identified on cameras that were separated by 1.68 ± 1.53 km.

Of 900 baits laid in front of camera traps, we were able to identify the fate of 346 baits (Table 4). We could not identify what taxa removed 170 baits, and 384 baits were not taken during the period that they were monitored. The known bait takes were recorded where animals were photographed picking up and removing baits, and from interpretation of other behaviours or physical evidence/sign captured on the time-lapse photos. For 54/94 (57%) of baits taken by varanids, there was evidence of them taking the bait through marks on the sand around the baits observed on the timelapse images. Similarly, small amounts of bait-take were attributed to raptors (four baits) and corvids (22 baits) because the birds were observed pecking at the bait in front of the camera when the cameras were triggered on time-lapse.

Significantly more baits were taken at the bait-naïve site (n = 305) than at the bait-exposed site (n – 211; $\chi^2_1 = 38.42$, $P < 0.001$). We could not confirm what species removed 129 baits at the bait-naïve site (29%) and 41 baits at the bait-exposed site (9%), with camera interference by cattle being a common issue for the bait-naïve site. In total there was no significant difference in bait take between toxic (n = 250) and non-toxic baits (n = 266; $\chi^2_1 = 1.16$, $P = 0.281$). Within each site there was also no significant difference between take of

Table 4. Fate of toxic (1080) and non-toxic (same meat but not injected with toxin) baits at bait-naïve (not baited in the previous 10 years) and bait-exposed (baited bi-annually for ~40 years) sites in the southern rangelands, Western Australia.

Species	Bait-naïve site			Bait-exposed site		
	Non-toxic	Toxic	% bait-take	Non-toxic	Toxic	% bait-take
Wild dog	9	5	3%	3	3	1%
Cat	0	2	1%	4	4	2%
Varanid	5	5	2%	43	41	19%
Corvid	64	55	26%	34	32	15%
Raptor[A]	11	20	7%	0	0	0%
Bird	0	0	0%	2	3	1%
Rabbit	0	0	0%	1	0	0%
Missed	68	61	29%	22	19	9%
Not taken	68	77	32%	116	123	53%
Grand total	225	225		225	225	

[A]Raptor bait takes included 24 baits taken by black-breasted buzzards *Hamirostra melanosternon*, four by little eagles *Hieraaetus morphnoides*, one by a brown falcon *Falco berigora* and two by an unidentified raptor.

toxic and non-toxic baits. At the bait-naïve site, 148 toxic and 157 non-toxic baits were removed ($\chi^2_1 = 0.82$, $P = 0.364$), and at the bait-exposed site, 102 toxic and 109 non-toxic baits were removed ($\chi^2_1 = 0.43$, $P = 0.508$).

Of the 900 baits available, bait take by wild dogs was very low at both the bait-naïve (14 baits = 3%) and bait-exposed (six baits = 1%) sites. Similarly, cats were only responsible for two bait takes at the bait-naïve site (1%) and eight baits at the bait-exposed site (2%). Birds were responsible for the most baits removed at the bait-naïve site (33%, compared to 16% at the bait-exposed site) while varanids took the most at the bait-exposed site (19%, compared to 0% at the bait-naïve site).

There was a significant difference in bait longevity between the two sites (Cox proportional hazards $z = 4.47$, $P < 0.001$) with 37% of baits remaining at each replenishing check (minimum 30 days after deployment) at the bait-naïve site compared to 59% at the bait-exposed site (Fig. 3). There were also marked differences in the time taken by different

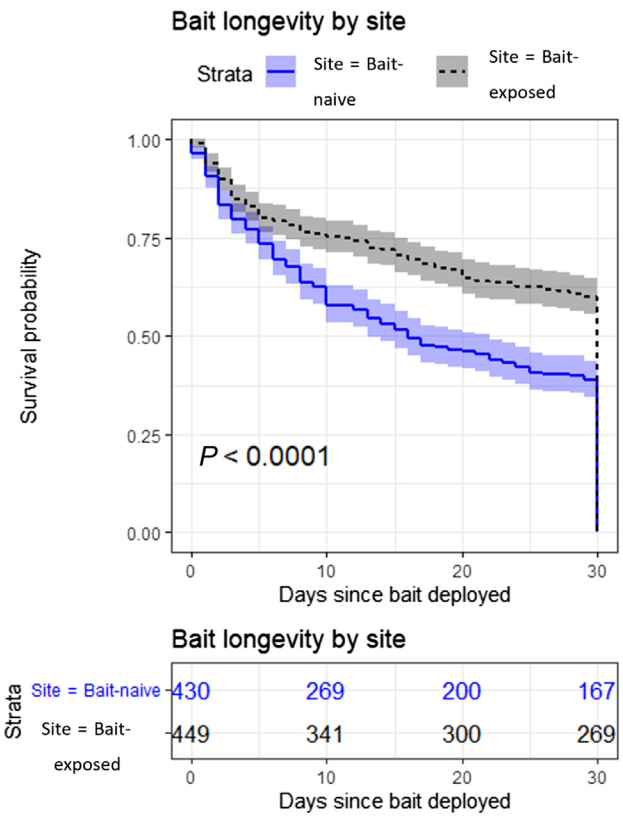

Fig. 3. Bait longevity for Study 1, comparing non-toxic and toxic (injected with 1080) dried kangaroo-meat baits at two locations in the southern rangelands of Western Australia, which either had a long history of baiting and classified as 'bait-exposed' (wild dogs were previously identified as 'bait-wary', Kreplins *et al.* 2018; Kennedy *et al.* 2021), or had no record of baiting for at least the previous 8 years (classified as 'bait-naïve' site). The data are truncated at 30 days, which was the minimum interval between camera servicing (the vertical line at 30 days reflects baits that were still on the ground at this time).

animal groups to remove baits. Corvids took the most baits ($n = 185$) of all species across both sites at an average of 15 ± 21 days. Compared with corvids, raptors (9 ± 22 days, $n = 31$, $z = 3.12$, $P = 0.002$) and varanids (10 ± 12 days, $n = 94$, $z = 2.62$, $P = 0.009$) were significantly quicker to take baits. Bait-take by cats (19 ± 14 days, $n = 10$ $z = 0.82$, $P = 0.413$) and wild dogs (16 ± 12 days, $n = 20$, $z = 0.50$, $P = 0.617$) was not significantly later than for baits taken by corvids.

Wild dogs were confirmed to take baits from 10 different camera trap stations at the bait-naïve site and three at the bait-exposed site. A total of 12 non-toxic and eight toxic baits were removed by wild dogs across the two sites; this difference was non-significant ($\chi^2_1 = 0.80$, $P = 0.372$). On 10 occasions across both sites, both a toxic and a non-toxic bait were available to a dog that visited a bait station and removed baits. On six of those occasions the wild dog took both baits, four times the non-toxic bait first and twice the toxic bait first. On the four other occasions when a wild dog only took one bait, the non-toxic bait was taken on three occasions and the toxic bait on a single occasion. Over these 10 occasions where both baits were available, a wild dog was equally likely to take a toxic bait as a non-toxic bait first ($\chi^2_1 = 1.60$, $P = 0.206$).

At the bait-exposed site, six baits were taken (three toxic and three non-toxic) compared to 14 taken at the bait-naïve site (five toxic and nine non-toxic). There was no significant difference in bait-type taken between the sites ($\chi^2_1 = 0.01$, $P = 0.921$). On three occasions at the bait-exposed site, both a toxic and a non-toxic bait were available. On two of those occasions the wild dog took both baits, once the toxic bait first and once the non-toxic bait first. On the remaining occasion, the toxic bait was taken and the non-toxic bait left (and was taken by a different wild dog later the same day). At the bait-naïve site, on seven occasions both a toxic and a non-toxic bait were available. On four of those occasions the wild dog took both baits, on three occasions the non-toxic bait was taken first and once the toxic bait was taken first. On the remaining three occasions when a wild dog took only one bait, the non-toxic bait was taken on all occasions. Overall, whether a wild dog was in the bait-exposed or bait-naïve site had no impact on whether a toxic or non-toxic bait was removed first ($\chi^2_1 = 0.82$, $P = 0.366$).

There was no difference in bait type taken by other species at each site or across the sites. Varanids took five toxic and five non-toxic baits at the bait-naïve site and none at the bait-exposed site. Corvids and raptors took 75 toxic and 75 non-toxic baits at the bait-naïve site and 32 toxic and 34 non-toxic baits at the bait-exposed site.

Discussion

Baiting programmes using 1080 are a major component of wild dog control in Australia and the continued effectiveness of

these programmes relies on understanding the mechanisms that attract or deter the consumption of those baits. Here we assessed the potential detection of 1080 as a cause of bait aversion in wild dogs. While the trials with a trained detector dog showed that 1080 was detectable by the dog, the dog was only successful in detecting 1080 in one of the four bait types tested (DOGGONE). The field trial showed no difference in bait-take for toxic and non-toxic baits, or between the bait-exposed and bait-naïve sites, although we could not determine if all baits were consumed. Results of this study suggest that 1080 is unlikely to be detected in most bait-types and not likely to be a cause of bait aversion.

Sodium fluoroacetate is often described as a tasteless and odourless compound (e.g. PestSmart 2020), a beneficial trait making it a desirable toxin as it is undetectable to pest species. While in its purest form it is odourless (Atzert 1972), Morgan (2004) found the commercial form (1080) to have a slight smell of vinegar due to acetic acid impurities. It has also been described as essentially tasteless with a mild salty, sour or vinegar taste (Atzert 1972), which may be detected in dilute solutions (Pelfrène 2010). With training, our detector dog was able to reliably indicate on filter paper containing commercial 1080 stock solution and discriminate it from filter papers containing the same solution without 1080. This demonstrates that there is some odour from 1080 solution that can be detected by a dog.

Our initial trials with the detector dog resulted in indications on filter papers containing the non-toxic and toxic solutions in equal amounts, suggesting that the dog was detecting a common element in both solutions, most likely the blue dye. The blue dye may have an odour that was initially more distinctive than the 1080 odour, as it took additional training to focus the dog on discriminating the 1080 from the dye. In practical baiting applications, the dye is present in the preparation of 1080 in fresh and manufactured baits as a condition of the label use, and so it would not matter whether a dog in the wild detected the dye or the 1080, it would be detecting the presence of the toxic solution in those baits.

The addition of bait material to our trials changed the detectability of 1080 for our detector dog. Our trained detector dog could still detect 1080 in DOGGONE but could not detect it in a CPE capsule, fresh meat or dried meat. This resulted in the dog indicating on empty pots, rather than non-target treatments; a result we believe to be an outcome of the training where the dog understood that food on its own was not a target odour, and so it was actively avoiding pots that it thought only contained foodstuffs (and not target odour). This behaviour prevented skewed results due to the chance that the dog had randomly indicated on pots with treatments in the hope of being rewarded.

Our field trials found no indication that wild dogs distinguish between dried meat baits with and without 1080. This was consistent in both the bait-exposed and bait-naïve sites. The 1080 solution in fresh meat, dried meat and CPE capsules either bound, trapped or masked the odour, preventing the dog from being able to detect it. Manufactured DOGGONE baits, however, still allowed 1080 odour to be present for detection by the dog.

While the use of a detector dog, with weeks of training to imprint the target odour of 1080, is not the same as using a free-roaming wild dog, it does provide a demonstration that 1080 is detectable by the species. A naïve wild dog on first encounter with a bait will not have negative connotations associated with that odour, if it is present. Some species, however, have demonstrated innate aversion to 1080 in baits. In laboratory trials, fat-tailed dunnarts (*Sminthopsis crassicaudata*) fed freely on non-toxic foods, but when those foods contained 1080, they were rejected, or consumption was greatly reduced (Sinclair and Bird 1984). Similarly, in New Zealand, brushtail possums (*Trichosurus vulpecula*) rejected carrots and pellets with 1080 at greater rates than when non-toxic (Morgan 1990). Both these species have evolved in the presence of plant species that contain fluoroacetate and therefore an innate aversion to 1080 may be expected. Morgan (1990) overcame this bait aversion by adding masking agents (i.e. cinnamon and orange essence), which resulted in very high bait uptake by individual possums that had previously rejected 1080 baits. Bait rejection has also been reported in field trials evaluating the risk of 1080 fox baiting using FOXOFF (a similar bait matrix to DOGGONE) on spotted-tailed quolls (*Dasyurus maculatus*), with baits being visited and, in some cases, removed but not being consumed (Körtner *et al.* 2003). These trials all used either baits with 1080 added to the surface of carrots or mixed into pellets (Morgan 1990), mixed into meat mince (Sinclair and Bird 1984) or the FOXOFF bait matrix (Körtner *et al.* 2003), which may have allowed the odour or taste of 1080 to be more detectable than if 1080 had been injected into meat and used fresh or dried. Indeed, Körtner (2007) found that 68% of radio-collared spotted-tailed quolls had consumed at least one fresh meat bait containing 1080, and that multiple bait consumption was common, with one quoll consuming six baits and surviving. This suggests that 1080 was not a deterrent to bait consumption in fresh meat baits.

Wariness to baits, or anything new in the environment (i.e. neophobia), could be innate in some dogs, or learned from cues from older dogs or their own experience (Allsop *et al.* 2017). These wild dogs are likely to be more difficult to control and may require additional management tools such as trapping or hunting. Inducing a learned aversion from a dog's own experience requires a negative action to have occurred (Allsop *et al.* 2017). For example, a wild dog that consumes a sub-lethal dose of 1080 and subsequently experiences sickness or malaise might learn to associate the illness with the bait – although the lag phase between ingestion and onset of signs of illness is increased at lower, sub-lethal doses (Goh *et al.* 2005), which may reduce the likelihood of association. If the odour of 1080 is associated with the bait, then subsequent 1080 baits encountered – where the 1080

could be detected – may be avoided. In our study, the detector dog had a positive outcome associated with 1080 odour (ball play) and so was incentivised to find the 1080 odour. However, the inability of the dog to detect the 1080 odour in the fresh meat, dried meat or CPE capsules suggests it is unlikely that 1080 odour is an identifying cue responsible for inducing learned aversions by wild dogs to those bait types.

Our study also highlighted the role of non-target species interference on bait availability for the target pest species. Wild dogs in our field trial removed less than 2% of deployed baits across both sites, which are similar to other invasive carnivore uptake rates of 1080 baits in other field studies in Western Australia (Dundas *et al.* 2014; Kreplins *et al.* 2018; Kennedy *et al.* 2021). Although studies in other states of Australia have demonstrated higher rates of bait removal by target animals, they have still reported significant removal by non-targets such as corvids (Allen *et al.* 1989) or rodents (Mason *et al.* 2025). In our study, raptors and varanids were much quicker at removing baits and took many more baits, as did corvids, than wild dogs (or cats). While these species are unlikely to be killed by the amount of 1080 consumed, due their lower sensitivity compared to introduced wild dogs (McIlroy 1984; McIlroy *et al.* 1985; Martin and Twigg 2002), the removal of baits reduces the opportunities for the target species to encounter baits.

Limitations of this study

We only assessed one detector dog for the detection of 1080 on filter paper and in bait matrices. This addresses the stated aim of determining whether it is possible for a dog to detect 1080 in isolation or in a bait. Results in other studies show very high consistency in detection rates between multiple dogs trained to detect the same odour (e.g. Porritt *et al.* 2015; Lazarowski *et al.* 2021; Waggoner *et al.* 2022). The experience of the trainer (CAM) in preparing multiple detector dog teams for detection of chemical residues and invasive ants is that once any dog is trained to industry accepted standard and has passed validation testing, they perform consistently in odour detection.

Designing cafeteria trials can be difficult. If the purpose is to determine attractiveness of baits, the simultaneous provision of multiple cues can make it impossible to distinguish cues that are attractive from those that are not. Our trials did not involve multiple differences between the bait options, only presence or absence of 1080, and when wild dogs removed baits, on most occasions they removed both baits with no difference in which was taken first, suggesting that (a) 1080 odour is not a cue to prevent a bait being taken or (b) the odour is not detectable from these baits (in line with the detector dog study). Therefore, we do not believe that odour confusion was a significant issue. Our trials with the trained detector dog also demonstrated that olfactory cues can be distinguished at distances closer than those presented in the cafeteria trial, albeit by a trained dog of a breed known for olfactory acuity. Attractiveness of different baits may be interpreted from which baits are removed or consumed first, although removal and consumption can also depend on which bait the animal encounters first, and when a favoured bait has already been removed, that choice is no longer available to the animal or other individuals that come across the cafeteria (Meier *et al.* 2012). Many bait-monitoring methods (e.g. sandpads) preclude being able to determine which cue attracted the animal to the 'cafeteria', or which bait was removed or consumed first. Some authors therefore advocate having baits spaced sufficiently far apart for each to be independent (e.g. Webster and Beasley 2019; Wales *et al.* 2021). Alternatively, it is possible to untangle differences between bait attractiveness with sufficient replicates, combinations of baits, distances between individual baits within a sampling station and appropriate monitoring methods. The camera traps we deployed allowed us to record removal of individual baits but not always consumption, and determine which bait was approached and taken first. The baits were also generally deployed perpendicular to the line of travel of the animal down the track, which should ensure that they had reasonably equal likelihood of being discovered first.

The physical act of monitoring itself, especially with camera traps, can also influence the outcomes of the study (Séquin *et al.* 2003; Meek *et al.* 2016). For example, some individuals are neophobic and will avoid novel scents, objects or sounds, including those issued by camera traps, with GPS-tracked individuals passing around cameras without being captured, while others appear to be attracted to the cameras – approaching and staring into the camera (Meek *et al.* 2014, 2016). For example, in a study nearby to our sites in the southern rangelands, wild dogs were seen an average of 13 ± 20 times over 16 months of monitoring, but the range was 1–142 times (Kennedy *et al.* 2021). Monitoring methods can therefore bias the study, and we acknowledge that bold animals or young naïve animals were more likely to approach baits monitored by camera.

In Western Australia, it is a legal requirement for landholders to manage wild dog populations on their properties as a declared pest species under the Biosecurity and Agriculture Management Act 2007 (BAM Act; https://www.agric.wa.gov.au/). It is therefore not common to find a property that has abstained from toxic baiting for a long period. We therefore could not repeat our trial over multiple properties but instead relied on individual wild dogs as the level of replication for this work. We deployed baits at camera trap stations stretching over ~35 km – a distance far greater than the distances between camera traps on which we identified known individual dogs (sightings separated by 1.68 ± 1.53 km). We also demonstrated substantial wild dog populations at each of the study sites, with 52 individuals recognised at the bait-naïve site and 32 individuals recognised at the bait-exposed site.

Conclusion

1. Our detector dog was able to detect the odour of 1080 at the levels present in wild dog baits. However, the dog was unable to detect the same amount of 1080 when injected into meat baits and presented either fresh or dried. The 1080 solution in CPE capsules was also undetectable to the dog. The presence of 1080 in wild dog baits is therefore not likely to cause initial bait aversion behaviour that would limit the efficacy of baiting programmes.
2. There could be any number of factors that cause a wild dog to decide to not approach or consume a bait. The act of placing a bait in the environment, especially by ground application, would provide vehicle scent (e.g. fuel and metal), human scent, track disturbance and other cues that may be important to a dog in a way that we cannot fathom. A wary dog could decide any such cue is reason to avoid the area. Other factors beyond the placing of a bait, such as food availability, may also affect the outcome of a bait encounter by a dog, e.g. a satiated dog can afford to be wary.
3. Bait availability is an important consideration for baiting programmes, as increased encounter rates should lead to increased consumption and kill rates. Only 37% of baits at the bait-naïve site were still present after one month, compared with 59% for the long-term baited (bait-exposed) site. Most of our bait removals were attributed to corvids and varanids, making them unavailable to wild dogs. Further research is needed into making baits less attractive to non-target species or evaluating timing of bait deployment to reduce encounter by non-target species and improve bait availability for wild dogs. Increased attractiveness and palatability of baits to wild dogs may also improve bait uptake rates, following encounter.
4. Future research could also examine aspects of wild dog movement, behaviour and activity during baiting programmes to assess the influence of different components of the baiting programme on wild dog uptake of baits. These components include human activity and movement, bait deployment, baiting rates and time and duration of bait deployment.

Supplementary material

Supplementary material is available online.

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Data availability. Data for Study 1 are presented in the manuscript and supplementary material. For data on Study 2, please contact the authors.

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