Biological Conservation 284 (2023) 110214

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/biocon

Review

Baiting in conservation and pest management: A systematic review of its global applications in a changing world

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ARTICLE INFO

Keywords:
Toxin
Pest
Canid
Felid
Population control
Rodent

ABSTRACT

Baiting is a powerful tool used to manipulate wildlife populations and induce ecosystem change. It involves delivering a substance to target individuals by deploying baits that they then consume. To identify patterns in bait applications and highlight opportunities for its improvement, we conducted a worldwide systematic review. Baiting occurred across 28 countries, but 60 % of all bait applications occurred in Australia or New Zealand. Baiting reports accelerated considerably in the early 2000's, driven by the use of sodium monofluoroacetate, which accounted for 42 % of all substances delivered in baits. For 89 % of bait applications their purpose was lethal control. Over 71 species were targeted in bait applications, including 62 mammals, eight birds and one reptile. Geographically, omnivores were the most widely baited guild, with carnivores being heavily targeted in Australia. Sixty-three percent of bait applications used simple designs that are known to frequently mis-represent the magnitude and direction of population impacts. The replication of impact and control sites was often very low. The distribution of baits occurred over areas as small as 100 m^2 and as large as 4000 km^2. Despite its overwhelming use for lethal control, baiting is not inherently detrimental to target individuals, and is also used to achieve therapeutic benefits. Baiting is an important tool that can be used to manipulate wildlife populations and induce ecosystem change; this power brings forth a responsibility to continually optimise its use and ensure its application is targeted. We highlight opportunities where the application of baiting may be expanded, and studies improved.

1. General introduction

Baiting involves delivering a substance to target individuals by deploying baits that they then consume. The bait media itself is a food product, often specifically designed to maximise its consumption by the target species (Cowled et al., 2006; Johnston et al., 2020; Rowley, 1963). The core objective of baiting is typically to poison or vaccinate individuals of a target species. Due to its ease of application, baiting is used by many wildlife and land managers worldwide, including researchers, government officials, industry, and private landowners (Allen, 2019; Baldwin et al., 2019; Bengsen, 2014).

Baiting is a powerful wildlife management tool used worldwide for conservation and pest management purposes. It is the most significant method through which almost all (>99 %) invasive rodent eradications are achieved on islands worldwide, and an important contributor to approximately one third of global cat (*Felis catus*) eradications (Campbell et al., 2011; Howald et al., 2007; Nogales et al., 2004). Furthermore, failure to eradicate invasive rodents from islands has been attributed to insufficient baiting (Samaniego et al., 2021). Baiting is an important method for managing invasive species, and consequently biodiversity conservation in both Australia and New Zealand (Murphy et al., 2019; Reddiex et al., 2006). Similarly, baiting contributes to the conservation of prairie dogs (*Cynomys* spp.) in the United States through the delivery of an oral sylvatic plague vaccine, and protecting the health of Alaskan wolves (*Canis lupus*) through the delivery of an oral antiparasitic to prevent and treat introduced biting dog lice (*Trichodectes canis*) (Gardner et al., 2013; Rocke et al., 2017).

Baiting can be highly effective at eliciting a desired response in the

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https://doi.org/10.1016/j.biocon.2023.110214
Received 5 May 2023; Received in revised form 20 July 2023; Accepted 25 July 2023
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target population. It is also advantageous because it can be easily applied across large areas at low-cost relative to other management tools. For example, it has been used to deliver substances to entire populations and is routinely used to deliver substances to large proportions (>80 %) of the target population (Baldwin et al., 2017; Ballard et al., 2020; Moseby et al., 2021; Saunders et al., 1990). Baits can be distributed at small local scales (<1km^2) or dropped from aircraft to cover much larger areas, with coordinated baiting programs commonly exceeding multiple thousands of square kilometres within a single continuous region (Allen et al., 2013; Ballard et al., 2020). There are few other wildlife management techniques, applied globally, with which it is practical or possible to access such large proportions of a target population at such large spatial scales.

Despite the demonstrated value of baiting as a population management tool worldwide, it attracts controversy (Berger, 2006; Doherty and Ritchie, 2017; Wallach et al., 2009). This is partially due to baiting frequently being used to achieve the lethal control of a target species. For example, compassionate conservationists are often opposed to lethal control in any form, and others argue that the lethal control of key predators, predominately achieved through baiting, has changed entire ecosystems, including fauna and flora assemblages and vast land forms (Lyons et al., 2018; Mills et al., 2021; Wallach et al., 2015). Poison baiting used for lethal control also comes with inherent non-target risks, whereby individuals of undesired or unintended species may consume baits and can experience lethal effects (Spurr and Powlesland, 1997). Although, the non-target impacts of baiting can be difficult to quantify in a robust manner, and consequently the extent to which they occur is not always well-known (Fancourt et al., 2022). Baiting can also pose risks to domestic animals, and the humaneness of toxic substances delivered in baits is often debated (Goh et al., 2005; Sherley, 2007). Thus, it appears there are both baiting advocates and critics, the opinions of which likely all vary depending on the specific substance being delivered, species being targeted or context in question.

In order to resolve controversies, refine and improve baiting as a method of wildlife management in conservation and pest management, it is first important to the understand basic information regarding the practice of baiting. Many fundamental questions regarding the practice of baiting are still not well-known, for example where, when and how baiting is used, what species are targeted, what substances are delivered, where these studies occur, how are they conducted, and over what time scales? Here, we conduct the first qualitative systematic review of the baiting literature to improve our understanding of such basic and fundamental questions. Given that baiting is an important tool in conservation and pest management practices, our intention is to summarise the literature, facilitate the identification of knowledge gaps and opportunities to improve practices, assist in directing research efforts, and foster improved decision making by wildlife practitioners. Such decisions are becoming increasingly more important in a changing world where invasive species and disease outbreaks are becoming most costly globally.

2. Methods

In the reporting and description of our methods we follow the MeRIT guidelines (Nakagawa et al., 2023).

2.1. Systematic literature search and collation

PLT first conducted a scoping search in Google Scholar with input from PT, KKP and DWAN, and identified 15 core articles that met our initial inclusion criteria (Appendix S1). Using the titles and abstracts of these articles PT and PLT created word clouds in the R package *wordcloud* version 2.6 to highlight key search terms of interest (Fellows, 2018). Refining our question, search criteria and core articles was an iterative process.

For our final literature search, we systematically searched titles and abstracts contained within all databases of the Web of Science, and titles, abstracts, and keywords within the Scopus database. This was largely done by PT with assistance form PLT and input from KKP and DWAN. These databases were selected due to being recommended by others as suitable for systematic review (Gusenbauer and Haddaway, 2020). Our final literature search was conducted on 14th September 2021, and was restricted to retrieve articles published between 1st January 1950 and 31st December 2020, inclusive.

PT refined our search string systematically with assistance form PLT by including or excluding terms one at a time and recording the number of articles retrieved and the number of core articles captured (Appendix S1 and S2). Our final search string is available in Appendix S2; it included four main terms, the first focused on capturing baiting studies, the second focused on capturing studies within the fields of conservation or pest management, the third focused on capturing field studies as opposed to laboratory or simulation studies, and the last search term was constructed to remove common themes that were not of interest. Our final search returned 4322 articles in total from both Web of Science and Scopus, and 13/15 (86.67 %) identified core articles, although all core articles were included in full-text screening and data extraction (Fig. 1). Web of Science returned a total of 1805 articles and 7/15 (46.67 %) core articles, and Scopus returned a total of 2517 articles and 13/15 (86.67 %) core articles.

PT imported all articles into Endnote X9.3.3 and removed 1056 duplicate articles. The remaining articles were then imported into Rayyan and a further 353 duplicates identified and removed (Ouzzani et al., 2016). An additional 19 duplicates were identified and removed manually by PT as titles and abstracts were screened. This left 2894 articles to be screened at the title, abstract and keyword stage. We assessed each article against our inclusion criteria and removed those that did not meet these criteria. Initial screening of all articles was conducted by PT. PLT then re-screened all articles identified for inclusion by PT; the authors disagreed on the inclusion of 7 articles, which were discussed until a mutual agreement was reached. We deemed 352 studies appropriate for full-text screening.

We expected grey literature to contain useful studies of relevance on baiting. However, it is extremely challenging to obtain such articles and reports as they are often not published or easily accessible. Google Scholar has been shown to be a powerful tool to supplement searches in Web of Science and Scopus to capture more of the grey literature (Haddaway et al., 2015). As such, we supplemented our systematic searches in both Web of Science and Scopus with an equivalent search in Google Scholar. This search was conducted on 20th February 2023 and returned 114,000 hits (Fig. 1); our equivalent search string can be found in Appendix S2. PLT reviewed the first 300 hits in Google Scholar, following recommendations by Haddaway et al. (2015), for articles or reports of interest that were not captured by Web of Science or Scopus. All these 300 hits were screened at the title, abstract and keyword stage, and if possibly of interest were matched back to our Web of Science or Scopus results to identify duplicates. This identified an additional 30 articles/reports for full-text screening.

Our literature search did not extend beyond English language. However, we acknowledge that many studies within the field of conservation are published in languages other than English (Amano et al., 2023; Amano et al., 2021). We therefore encourage readers to interpret our results accordingly.

2.2. Inclusion criteria and full text screening

To be included in our systematic review studies: 1) had to use a food product to deliver a substance to a non-human terrestrial vertebrate; and 2) needed to show that at least one species subsequently consumed the product containing the substance to be delivered. We excluded studies where the bait used contained only biomarkers, attractants, or deterrents, and was not intended to deliver a toxic or therapeutic substance to the target species. We also excluded studies that were conducted

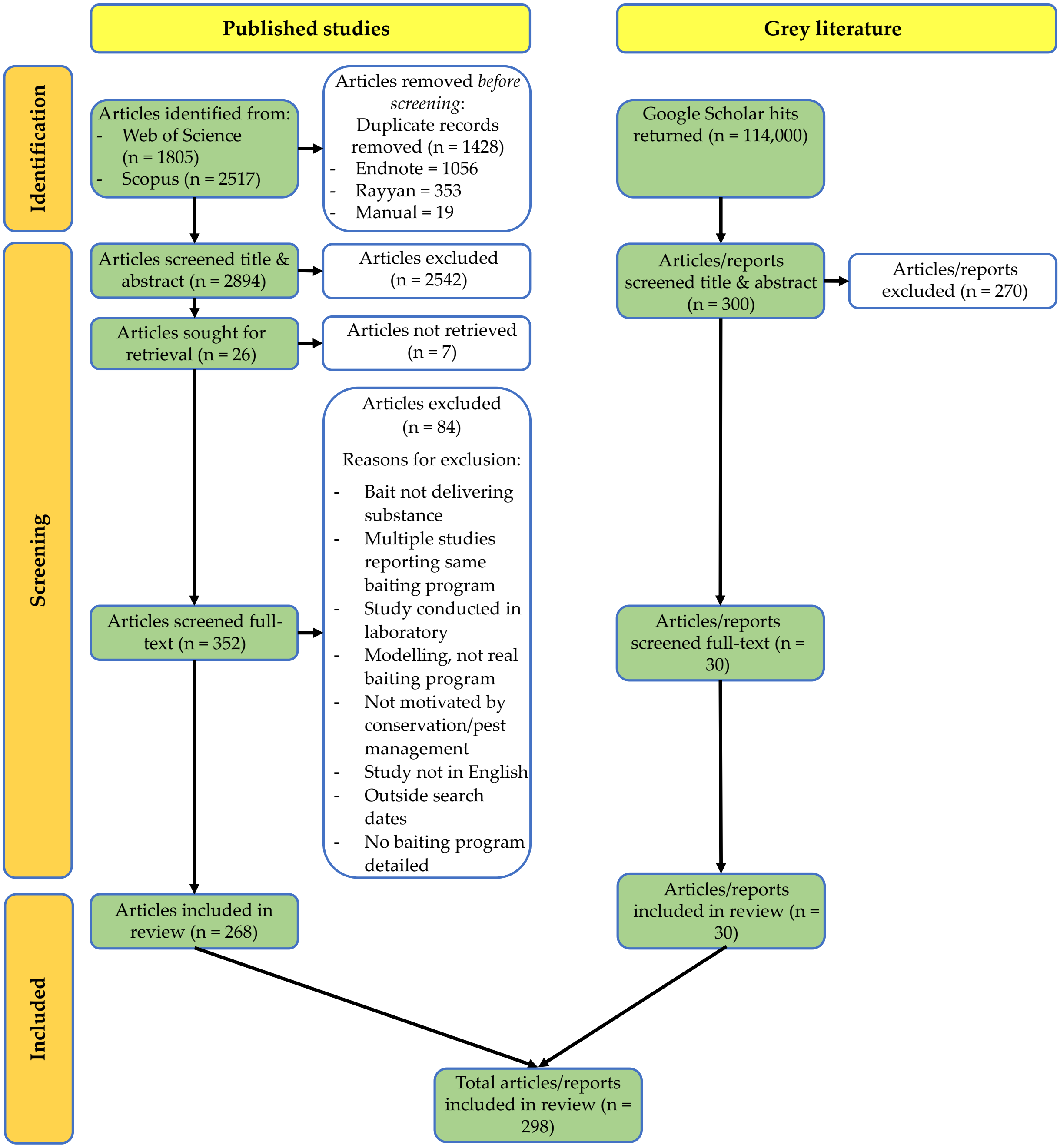

Fig. 1. Modified PRISMA diagram showing the search process and the number of articles considered at each step (orange boxes). For each step, green boxes represent articles/reports included and unfilled boxes represent articles excluded.

purely in the laboratory, and studies that were not driven by conservation or pest management motives. For example, baits are commonly used to mitigate rabies transmission in wildlife populations via the oral delivery of a vaccine (Cliquet et al., 2007; Wallace et al., 2020); however, such studies are sometimes purely motivated by human health outcomes. In contrast, similar studies that were driven by conservation motives were retained – for example, studies that use baits/oral vaccines to mitigate disease in wildlife populations for the benefit of the species itself (Gardner et al., 2013; Rocke et al., 2017).

Full-text screening was conducted by both PT and PLT, however PT screened the majority of articles (~80 %). For a sub-set of articles (30 articles), both PT and PLT reviewed the same articles to compare and confirm that both authors were extracting equivalent data. Additionally, both PT and PLT thoroughly reviewed the final dataset of extracted data for anomalies, which were amended as appropriate. We excluded 84 articles retrieved from Web of Science or Scopus during the full-text screening process for various reasons, including baits not delivering a substance, the same baiting application being reported on by different studies and studies being solely conducted in the laboratory, among other reasons (Appendix S3). This gave a total of 268 articles retrieved from Web of Science or Scopus from which data were extracted, and an additional 30 articles/reports identified for data extraction through Google Scholar. Our literature search aimed to capture a representative sample of the baiting literature. However, we appreciate that baiting is a very practical and applied management technique, with many routine bait applications conducted by government or private land managers likely going undocumented or not reported on in any formal manner. Therefore, in an attempt to quantify this possible bias, we extracted information relating to the broad classification of the first and last authors' primary affiliation (i.e. government, academic, industry or non-profit organisation).

2.3. Data extraction

PT extracted information from each article with assistance from PLT. All information was extracted at the baiting application level, as many articles describe multiple separate bait applications. We defined a single bait application as baiting that was conducted using consistent methodology over a continuous time period. In this context, an article was taken to represent multiple bait applications if the baiting was conducted:

- Over a discontinuous time period in which two or more bait applications were expected to result in distinct pulses of bait consumption and separate and distinct pulses of impact on the target population. Substances delivered in baits often degrade quickly and a majority of bait uptake occurs rapidly, within 1–7 days (Brown et al., 2002; Brown and Singleton, 1998; Claridge and Mills, 2007; Dundas et al., 2014; Gentle et al., 2007; Kreplins et al., 2018; McIlroy et al., 1986; Saunders et al., 2000; Sutherland and Singleton, 2003; Twigg et al., 2007). Consequently, some operations were classified as separate programs if bait applications were separated by two weeks, although most bait applications were separated by one month or more.
- Using different baits. For example, if different toxin concentrations were used or if the same toxin concentration was used with a different bait matrix/ingredients.
- Using different study designs. For example, if baits were applied at different densities, or if a before-after study design was used at one site and a randomised controlled design was used at another site.

For each article we extracted: (i) the target species and number of species targeted; (ii) the substance being delivered in the bait; (iii) the bait type and state (solid, semi-solid, other); (iv) the bait media and ingredients; (v) the purpose of the bait; (vi) how the bait was produced; (vii) how the bait was distributed; (viii) how the bait was positioned (on the surface of the ground, buried below the ground, in a bait station, down the target species burrow, other); (ix) if a non-toxic lure, separate to the bait but deployed simultaneously, was used to attract the target species to the location of the bait; (x) if a non-toxic food that replicated the bait was deployed prior to the deployment of the real bait (i.e. was pre-feeding conducted), and for how long; (xi) the study location; (xii) records of bait consumption or interference by non-target species, and the number of non-target species documented; (xiii) the baiting density; and (xiv) the design of the baiting study (observational study: bait delivered to target individuals and its impact observed; before-after study: target individuals monitored prior to and after baiting treatment; control-impact study: subset of target individuals subject to baiting treatment and subset subject to non-active baiting treatment or no baiting treatment at all, no treatment randomisation; before-after-control-impact study: baiting treatment individuals and non-active or no baiting treatment individuals monitored before and after baiting; randomised controlled study: equivalent to control-impact study with randomisation of treatments).

All extracted data are available in Appendix S4. We use descriptive statistics to describe and summarise the qualitative information extracted. All descriptive statistics were conducted by PLT with input from DAWN and KKP in R 4.0.2 and plots created in the package *ggplot2* version 3.3.2 (R Core Team, 2022; Wickham, 2016). Full dataset extracted, along with meta-data, appendices and R code to reproduce results can be found on the Open Science Framework at https://osf.io/wb97u/. We did not conduct any quantitative synthesis of the literature due to wide variation in the question addressed by studies, the outcome variables measured and the degree to which studies focused on and reported baiting related information. We deemed it more appropriate to focus on quantitative meta-analysis of specific subsections of the baiting literature in separate texts.

3. Results

3.1. What substances are delivered in baits?

We identified 2223 separate bait applications across the 298 articles included in our review. These bait applications delivered at least 46 different substances (Fig. 2; not all studies adequately described the substance that their bait was delivering). Sodium monofluoroacetate was the most frequently delivered substance, accounting for 42 % of all substances delivered in baits. Brodifacoum was the second most frequently delivered substance, followed by zinc phosphide, sylvatic plague vaccine and strychnine, which each accounted for 7 %, 6 %, 6 % and 4 % of all substances delivered in baits respectively.

The vast majority of baits (89 %) delivered toxins for the lethal control of the target species. The second most common bait purpose was vaccination, accounting for 6 % of applications, followed by immobilisation, accounting for 2 % of applications. The metabolic poison, Sodium monofluoroacetate, was the most frequently delivered toxin and accounted for 46 % of all toxins used. First (15 %) and then second generation (13 %) anticoagulants were the next most frequently used toxins. The sylvatic plague vaccine was almost the sole substance delivered for the purpose of vaccination and accounted for 95 % of bait applications for this purpose. The narcotic, alpha-chloralose was the only substance delivered for the purpose of immobilisation.

Twenty-five of the 46 substances were used in less than ten bait applications and 23 substances were used in five or less bait applications. Most studies (99 %) delivered a single substance in each bait. However, 2 different substances were delivered in a single bait on 30 occasions; these substances were largely a combination of first and second generation anticoagulants or asphyxiants (26/30 occasions) and were typically, but not always, for the lethal control of rodents or other small mammals.

3.2. What species are targeted by baiting?

We identified at least 71 different species that were targeted in bait applications (Fig. 3). These species belonged to 26 families and 3 animal classes. In total we documented the baiting of 8 species of bird and at least 62 species of mammal. Only a single reptile was subject to baiting, the brown tree snake (*Boiga irregularis*) on the island of Guam, United States territory.

Mammals were the most frequently baited animal class, comprising 94 % of all species targeted in bait applications. Within Mammalia, murids were the most frequently baited family (45 %; 1416 bait applications), followed by canids (15 %; 464 bait applications) and then Leporidae (9 %; 286 bait applications) - with only one representative from this family, the European rabbit (*Oryctolagus cuniculus*). Only eight species were targeted in >100 bait applications; these were red fox (*Vulpes vulpes*), European rabbit, common brushtail possum (*Trichosurus vulpecula*), black rat (*Rattus rattus*), house mouse (*Mus musculus*), lesser bandicoot rat (*Bandicota bengalensis*), domestic cat, and brown rat (*Rattus norvegicus*).

The most frequently baited birds were the rook (*Corvus frugilegus*) and the feral pigeon (*Columba liva domestica*). Many animals were targeted only in few bait applications. Most bait applications (75 %) targeted a single species, but in some applications up to 8 species were targeted at once with the same bait. Most animals targeted in bait applications were omnivores (64 %) or carnivores (24 %). Many fewer animals targeted in bait applications were strictly herbivores (12 %).

Eighty-four of the 298 (28 %) articles included in our review reported bait interference or consumption by non-target species. One hundred and twenty-eight different non-target species were reported across all articles (Appendix S5). Despite mammals being the major taxa

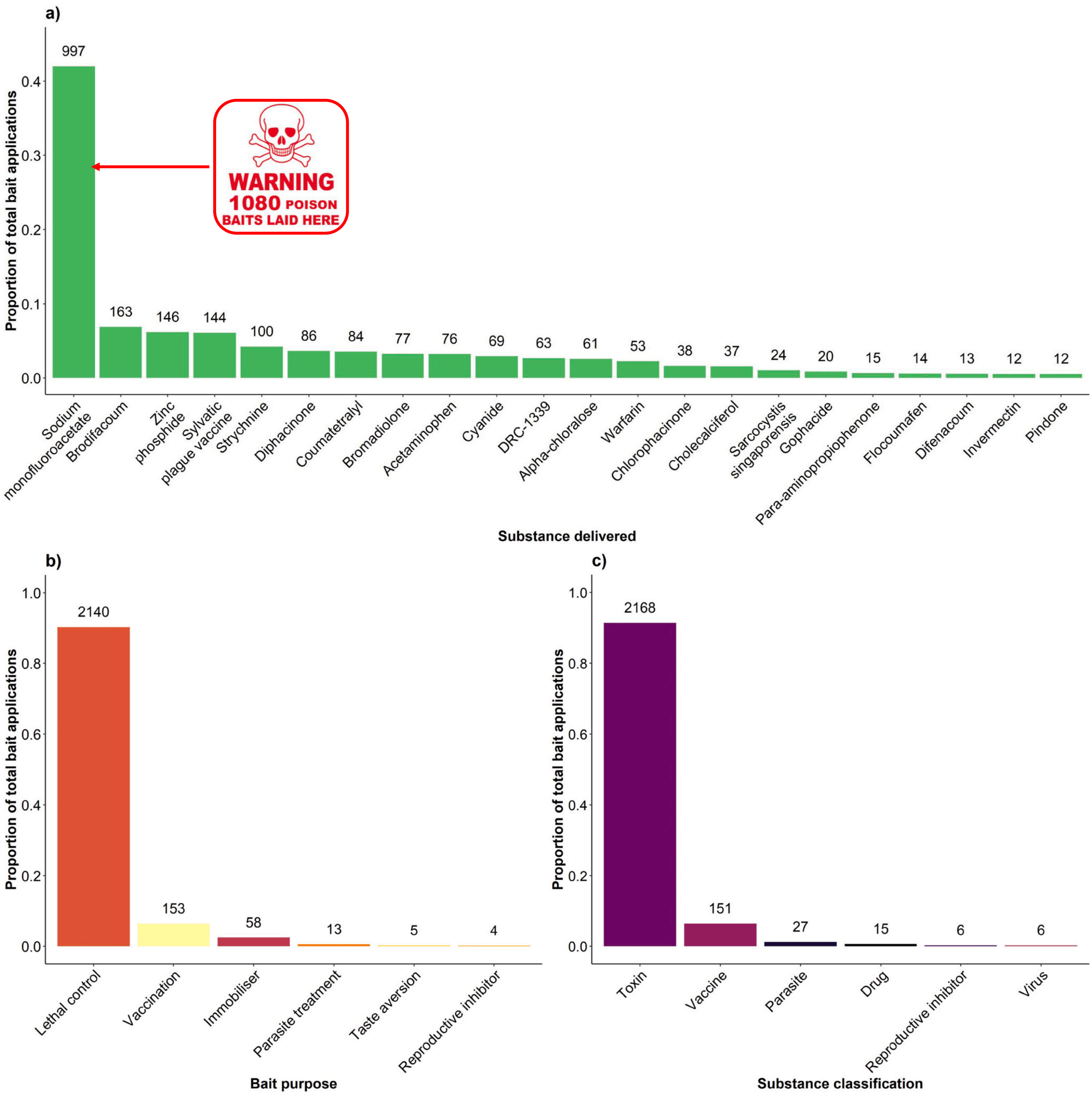

Fig. 2. Proportion of total baiting programs by substance delivered (a), bait purpose (b), and substance classification (c).
Numbers above bars represent the total number of baiting programs that used that substance. Note that in a) all substances that were delivered in baits in ≤10 baiting programs are not displayed; for the complete figure with all substances displayed, irrespective of their frequency of use, refer to Appendix F1.

that were targeted in bait applications, most non-target species reported were birds (54 %), followed by mammals (38 %), reptiles (4 %), crabs (1 %) and amphibians (1 %). When non-target species were reported, a median of 1 non-target species was reported (range: 1, 13). However, not all articles demonstrated the non-target species to have consumed the bait and those articles that did demonstrate bait consumption by non-target species did not always demonstrate impacts on the non-target individuals.

3.3. How are baiting studies designed?

We classified 6 % of bait applications as following an observational study design, 53 % as following a before-after design, 4 % as following a control-impact design, 27 % as following a before-after-control-impact design, and 10 % as following a randomised controlled design. The number of impact and control sites per bait application was low, with a median of only 1 (range: 1, 66) impact site and 0 (range: 0, 98) control sites.

Approximately half of the baits used were produced commercially (52 %), with the other half being produced in-house (48 %). Most baits were distributed by hand or terrestrial vehicle (79 %), with the remainder being distributed aerially. One bait application, studying the impact and humaneness of a substance on the target species, delivered the baits directly into the mouth of the target species. Few bait applications used a lure (1 %), and most did not do any pre-feeding (75 %). Of the bait applications for which we could broadly classify the first authors

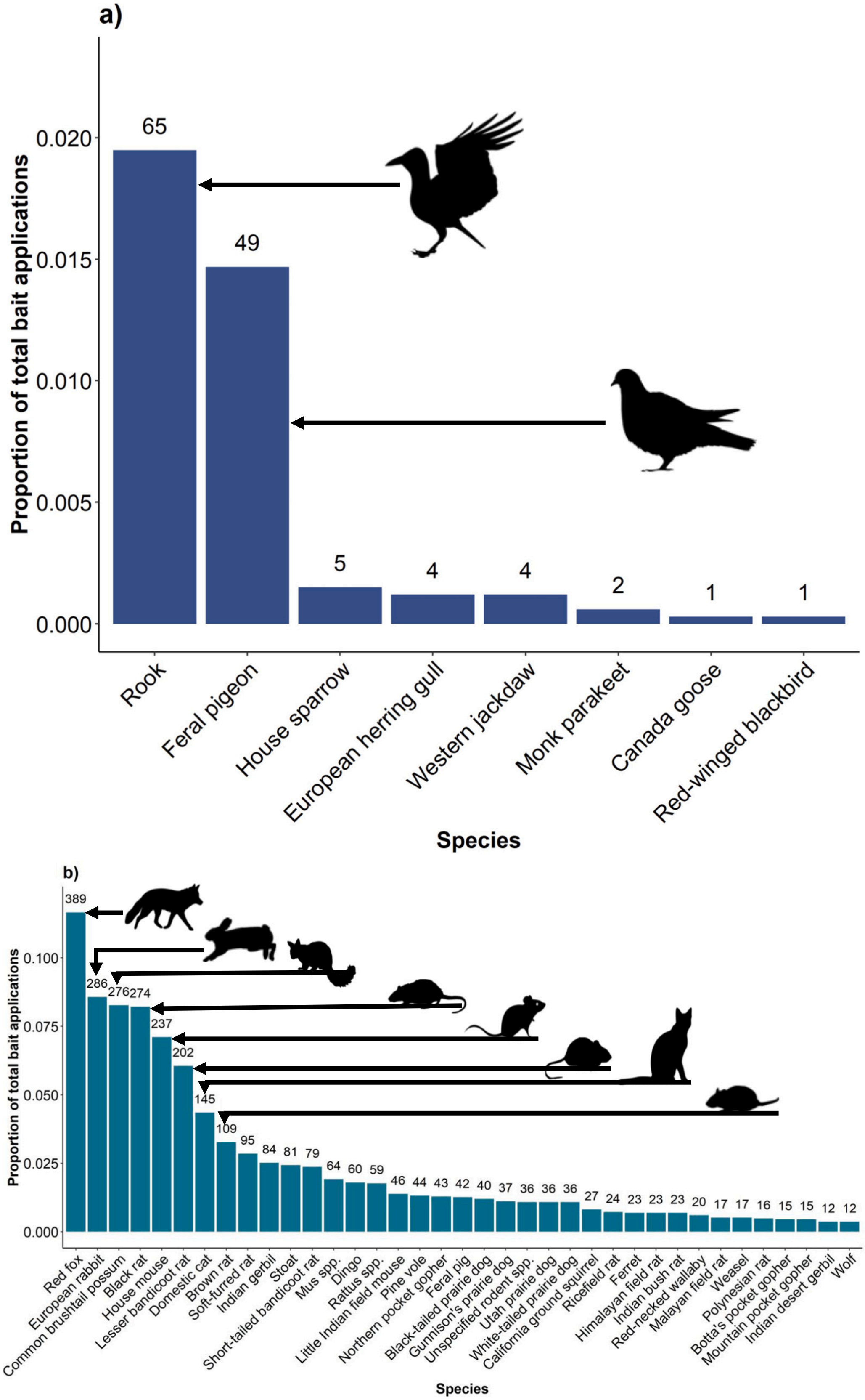

Fig. 3. Proportion of total baiting programs targeting birds (a) and mammals (b).
Numbers above bars represent the total number of baiting programs that targeted that species. Note that in b) all species that were targeted in ≤10 baiting programs are not displayed; for the complete figure with all species displayed, irrespective of the frequency with which they were targeted, refer to Appendix F2. All silhouettes obtained from https://www.phylopic.org/.

organisation, the majority were led by government organisations (67 %), followed by academic (24 %), industry (7 %) and non-profit (1 %) organisations.

3.4. Where does baiting occur?

We documented baiting in 28 countries worldwide. However, 60 % of bait applications occurred in Australia (879/2223) or New Zealand (457/2223) (Fig. 4). There were four other countries in which we documented >100 bait applications: United States (316), England (157), India (143) and Pakistan (117). We documented ≤36 bait applications in all other countries. Nine percent of bait applications (187/2223) occurred on islands. These bait applications were largely in association with the management or eradication of one or more of rodents, domestic cats, rabbits, common brushtail possums or brown tree snakes (Guam only); these applications covered 31 separate islands within the territories of ten different countries.

The total area over which baits were distributed in a single bait application varied enormously. The median area over which baits were distributed in a single application was 1.1 km^2, however, some bait applications distributed baits over areas as small as 10 × 10 m (0.0001 km^2), and others distributed baits over areas as large as 4000 km^2.

Baiting was used to target mammals in every country in our sample. However, birds were only targeted in England, New Zealand and the United States, and reptiles were only targeted on the island of Guam, United States territory.

The distribution of the target species guild was highly clustered (Fig. 4). Carnivores were only baited in 6/28 countries; 70 % of bait applications targeting carnivores occurred in Australia, 18 % occurred in New Zealand, and 11 % occurred in the United States. The contribution of the other three countries to the baiting of carnivores was minimal. Similarly, herbivores were only baited in 6/28 countries, with 60 % of bait applications targeting herbivores occurring in Australia, and approximately equivalent proportions (8–20 %) of bait applications targeting herbivores occurring across each of Canada, New Zealand, and the United States (in ascending order). The contribution of the other two countries to the baiting of herbivores was minimal. The baiting of omnivores was much more widely distributed (24/28 countries) but remained highly clustered across this wide distribution. Thirty-four percent of bait applications targeting omnivores occurred in New Zealand, 19 % occurred in India, 13 % occurred in the United States, 13 % in Pakistan, 8 % in England and 6 % in Australia. The contribution of all other countries to the baiting of omnivores was minimal.

Baiting was used for the lethal control of a target species in all countries identified except Ethiopia and Switzerland. This was in stark contrast to all other bait purposes, which occurred in very few countries. In addition to lethal control, baiting was used in the United States for parasite treatment, as a reproductive inhibitor, for taste aversion, and for vaccination; in England for immobilisation and as a reproductive inhibitor; in Switzerland for parasite treatment; and in Ethiopia for vaccination.

3.5. Is baiting a recently emerged wildlife management tool?

Despite the time period of our review ranging from 1950 to 2020, the earliest report included in our review was from 1961 (Fig. 5). The number of bait applications in our sample showed distinct peaks in the early 1980's and 1990's, before drastically increasing from the 2000's onwards. All peaks and consistent increases were associated with bait applications in Australia and New Zealand (Australian continent), for mammals, and for the purpose of lethal control. Similarly, these peaks and consistent increases in bait applications were also associated with high use of sodium monofluoroacetate.

Twenty-five substances and 36 species targeted were only done for a period of one year (Fig. 6). In contrast, eight substances, including zinc phosphide, warfarin and diphacinone, chlorophacinone, difenacoum, bromadiolone, brodifacoum and alpha-chloralose, and eight species, including rook, Polynesian rat, house mouse, brown rat, European rabbit, Indian gerbil, lesser bandicoot rat and dingo, featured in bait applications extending for periods of ~35 years or more. The use of at least seven substances (synthetic oestrogen (BDH 10131), 5-pchlorophenyl silatrane, calciferol, gophacide, pyriminil, flupropadine) and the baiting of seven species (feral pigeon, house sparrow, western jackdaw, meadow vole, pine vole, hairy-footed gerbil, sand-coloured soft-furred rat) had not occurred for >30 years.

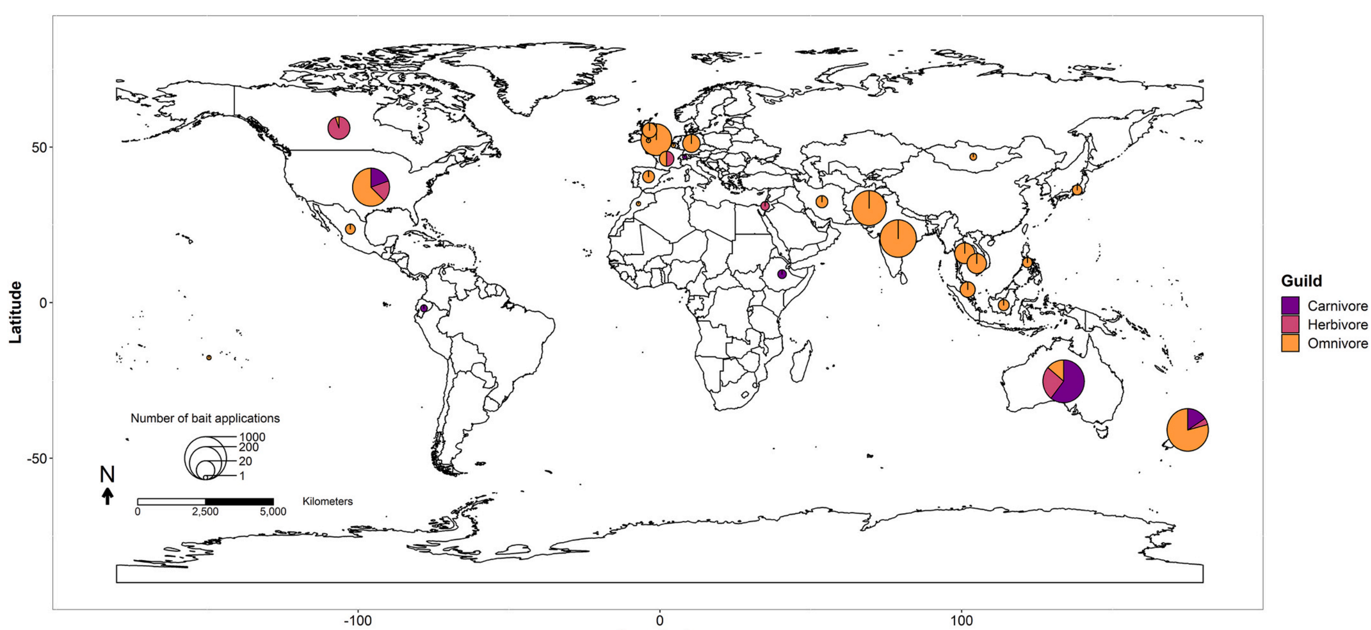

Fig. 4. Geographic patterns in the number of baiting programs by the target species guild. Number of baiting programs follows a log scale.

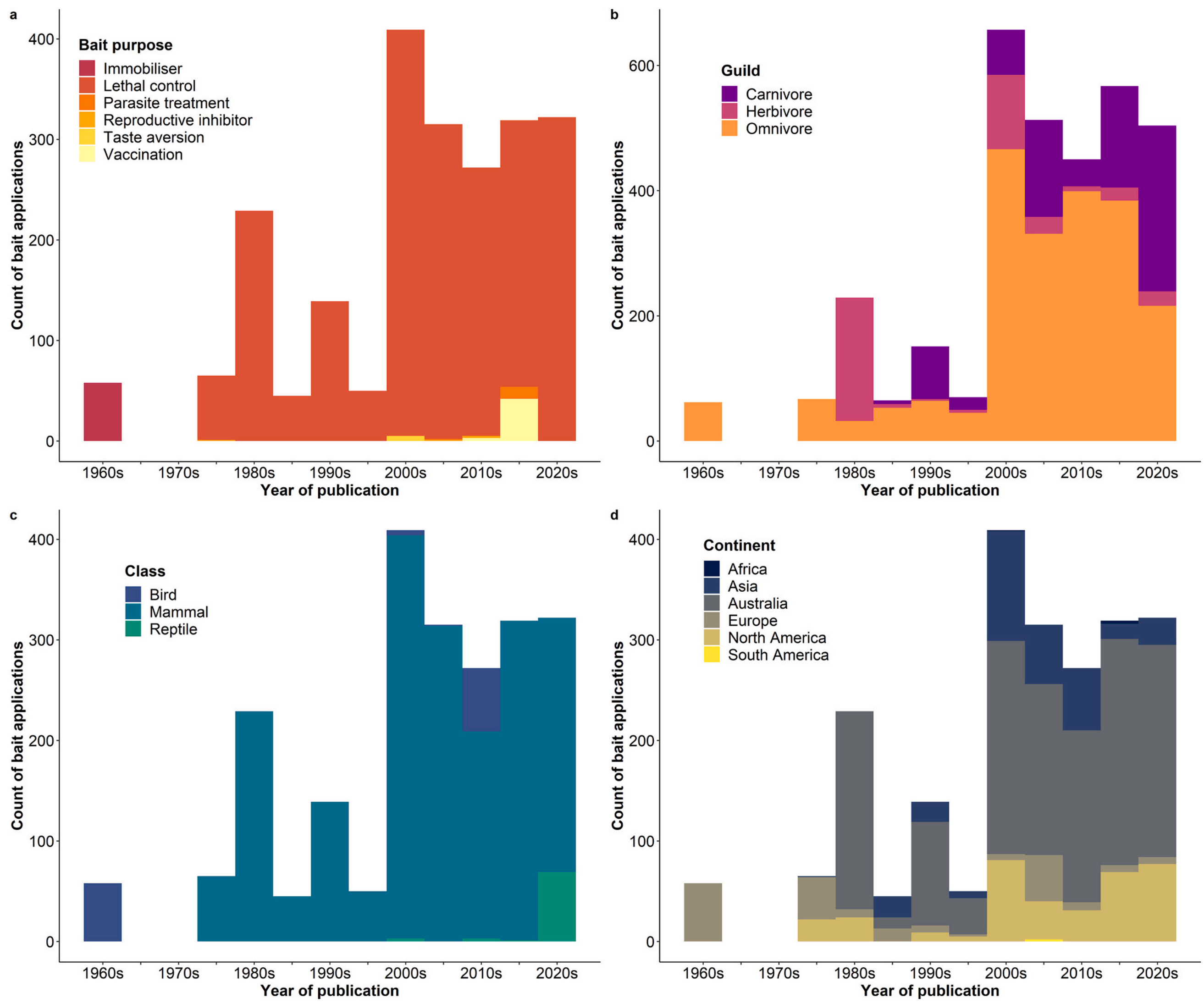

Fig. 5. Temporal patterns in baiting programs; a) count of baiting programs by year of publication and bait purpose; b) count of baiting programs by year of publication and animal guild; c) count of baiting programs by year of publication and animal class; and d) count of baiting programs by year of publication and continent.

4. Discussion

We provide the first major synthesis on how baiting is used by wildlife managers worldwide to achieve ecosystem change. Baiting has been used to deliver over forty-six different substances to more than seventy target species across birds, mammals and reptiles. The purpose of these bait applications can be to benefit target individuals and species, such as improving their health, welfare, or population survival, or it can be to manage or eradicate target individuals and species through their lethal control. Depending on the context, the impacts of baiting on targets can have profound outcomes for non-target individuals, species and ecosystems. As wildlife managers it is important that we critically appraise and continually improve the tools we employ to manipulate populations and induce ecosystem change. This is especially true for the most powerful tools in our toolbox, where appraisal and improvement are arguably of greater importance due to the wider reach of the tool itself. Baiting is one of these tools.

4.1. What substances are delivered in baits?

We documented the delivery of at least 46 different substances in baits. However, sodium monofluoroacetate (1080) was the most frequently delivered substance and accounted for 42 % of all substances delivered in baits. This was almost solely driven by its use in Australia and New Zealand, which combined accounted for 99.6 % of the total sodium monofluoroacetate use in baits. Both countries rely heavily on baits containing sodium monofluoroacetate to achieve the lethal control of vertebrate pests. This high prevalence of sodium monofluoroacetate use in baits in both countries can be attributed to a number of factors, including the high environmental and economic impacts of vertebrate pest, the effectiveness of the toxin itself, the higher tolerance of Australian natives to the toxin, and the fact that it is one of very few vertebrate pest toxins approved for aerial application (Bradshaw et al., 2021; Goldson et al., 2015; McIlroy, 1981; O'Malley et al., 2022).

The next most commonly delivered substances were all used with approximately similar frequency and included brodifacoum, zinc phosphide, sylvatic plague vaccine and strychnine, all of which accounted for 4 %–7 % of substances delivered. However, approximately half of all substances were delivered in <0.5 % of bait applications, likely demonstrating that only a fraction of trialled substances are incorporated into routine or ongoing management. Most trialled substances may see limited uptake, or their use discontinued, which can be unrelated to their demonstrated efficiency. For example, diazacon baits were trialled and successfully demonstrated to reduce reproductive output in monk

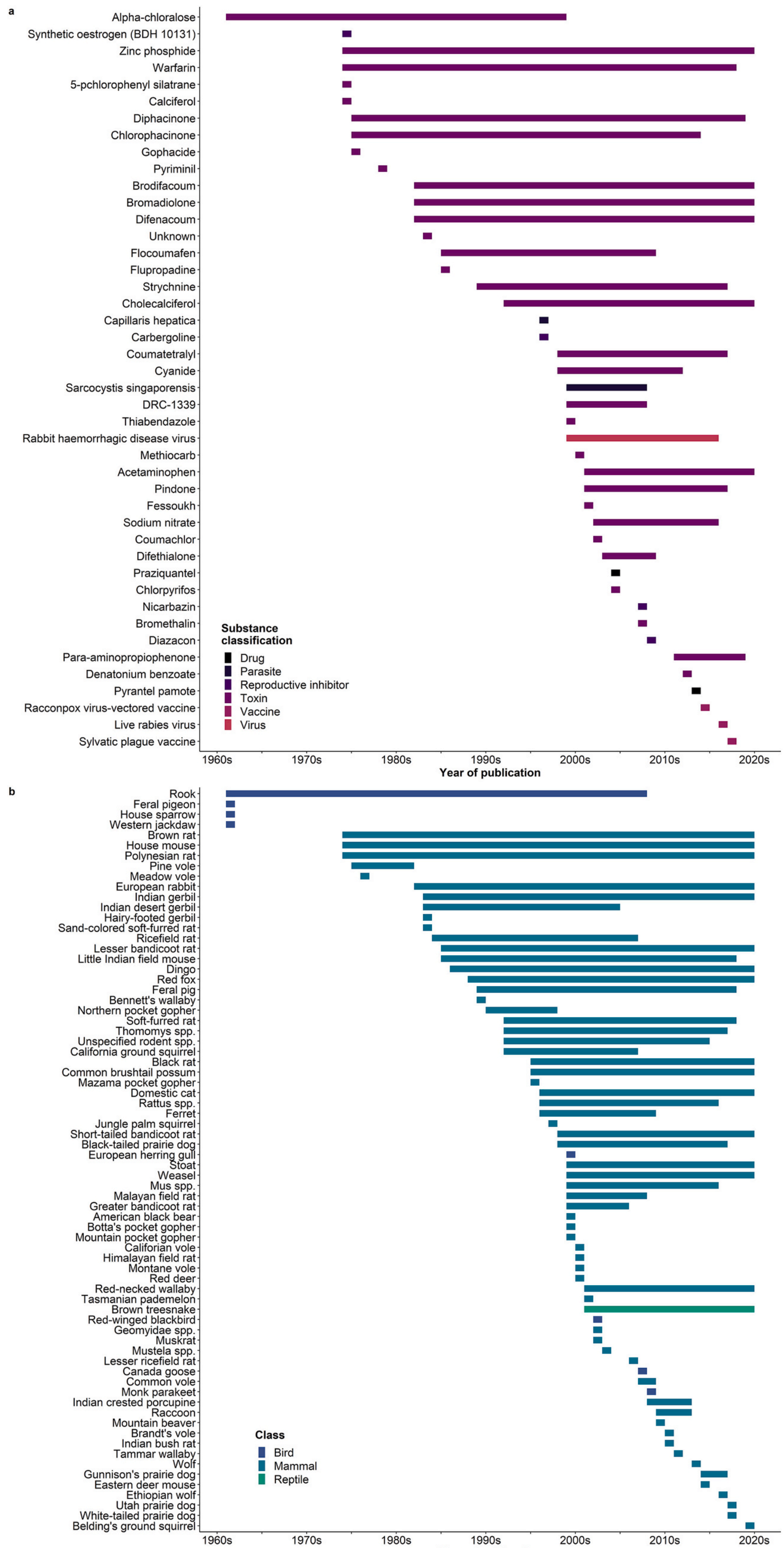

Fig. 6. Temporal patterns in baiting programs delivering specific substances (a) and targeting specific species (b).

parakeets in Florida, USA, but were never subsequently used to manage wild parakeet populations due to shifting priorities (Avery et al., 2008).

Substances delivered in baits were dominated by toxins. After the metabolic poison, sodium monofluroacetate, first- and second-generation anticoagulants were the next most frequently used toxins. Four of the top ten most frequently delivered substances were first- or second-generation anticoagulants. This may reflect the wide commercial availability of such toxins, particularly for rodent control, and the fact that some of these toxins are also among the very few that are approved for aerial distribution in some countries (O'Malley et al., 2022). While both first- and second-generation anticoagulants have been of great environmental benefit and have contributed significantly to the eradication of rodents from multiple hundreds of islands worldwide, secondary, non-target impacts of such toxins are only becoming appreciated and understood more recently (Campbell et al., 2011; Howald et al., 2007; Lohr and Davis, 2018; Nogeire et al., 2015; Thomas et al., 2011).

The dominance of sodium monofluoroacetate, first- and second-generation anticoagulants was consistent with the lethal control of a target species being the major bait purpose. Again, the use of these substances, with the purpose of lethal control, was strongly driven by baiting in Australia and New Zealand. The frequency of use of these potentially lethal substances gives them the greatest potential for adverse impacts (Brakes and Smith, 2005; Eason and Spurr, 1995; Mallick et al., 2016). While all these substances can and do have profound environmental and economic benefits in the appropriate circumstance, a high level of critical appraisal of their use is necessary and justified given their potential lethality and frequency of use. Indeed, non-target impacts associated with the use of these toxins has been a key area of research, and substantial improvements have been made through iterative changes to bait size, colour, ingredients, and methods of deployment, as well as legislative updates to enforce best practice (Australian Pesticides and Veterinary Medicines Authority, 2008; Eason et al., 2011; Eason and Spurr, 1995; Glen et al., 2007; National Animal Identification and Tracing, 2007). However, this continues to warrant research investment and scientifically informed legislative updates.

Despite toxins and lethal control dominating the baiting space, baiting itself is not inherently detrimental to target individuals or species. Baiting is a tool used to deliver a substance to target individuals and species and can also be used for their benefit. Consistent with this, vaccination was the second major bait purpose, with the sylvatic plague vaccine being nearly the sole substance delivered for this purpose. This vaccine is one of the major conservation tools used in the management of prairie dog populations in the United States (Creekmore et al., 2002; Elzinga et al., 2020). Although baiting is not widely used to benefit target individuals or species, in the face of declining threatened species populations and an increasing frequency of wildlife disease outbreaks, we see great opportunity to expand its use for purposes beneficial to target individuals and species, such as for parasite and disease management (Aguirre and Tabor, 2008; Brearley et al., 2013).

4.2. *What species are targeted by baiting?*

At least 62 species of mammal, eight species of bird and one reptile species were targeted in bait applications. Overall, the majority of bait applications targeted mammals, and in particular rodents, which were baited worldwide.

Mammals may be more readily targeted in baiting due to the greater number of invasive mammals relative to birds or reptiles, or their greater potential for destructive effects on ecosystems and economies globally (Bradshaw et al., 2021; Cuthbert et al., 2022; Haubrock et al., 2021; Jeschke, 2008). This would be expected to lead to mammal populations being more frequently subject to management and would be supported by lethal control being the primary purpose of baiting. Alternatively, mammals may be more readily targeted in bait applications due to a perception that they are more amenable to consuming baits. Mammals are often considered to have a highly developed sense of smell and are often readily willing to scavenge food (McGann, 2017; Sebastián-González et al., 2019; Sebastián-González et al., 2021). These are both traits that are exploited in baiting, which relies on the target species locating a stationary, and often scented, food product (the bait), and their willingness to consume/scavenge it.

It is possible that the propensity for birds and reptiles to take baits is underappreciated or partially untested. Birds and reptiles are often considered to be strongly visually motivated, and birds are commonly thought to have a rudimentary sense of smell. However, research clearly demonstrates the importance of olfaction to the ecology and life history of both birds and reptiles (Balthazart and Taziaux, 2009; Driver and Balakrishnan, 2021; Schwenk, 1993; Vandewege et al., 2016). Both taxa are also frequently documented scavenging, including the scavenging of baits, suggesting that they may scavenge more readily than appreciated (Aiyer et al., 2022; Bengsen et al., 2011; DeVault and Krochmal, 2002; Kreplins et al., 2018; Sebastián-González et al., 2019; Sebastián-González et al., 2021; Woodford et al., 2012).

Birds and reptiles also commonly establish invasive populations that require management. For example, the European starling and Indian myna are often subject to management in Australia, and large invasive constrictors and green iguanas are currently subject to management or pose an establishment risk within the United States (Grarock et al., 2014; Krysko et al., 2007; Reed and Rodda, 2009; Rollins et al., 2009). Similarly, birds and reptiles frequently suffer from parasites and diseases and populations can benefit from treatment. For example, self-fumigation in the forty-spotted pardalote (*Pardalotus quadragintus*) mitigates the impacts of parasitic nest flies (*Passeromyia longicornis*) and significantly increases nestling survival (Alves et al., 2021). Mucid flies (*Philornis downsi*) also threaten the survival and persistence of numerous bird species on the Galapogos Islands, including several species of Darwin's Finches, with a range of treatments having been trialled and some demonstrated effective in the short-term (Fessl et al., 2018). Baiting is one method through which such population manipulations may be achieved in birds or reptiles, but has possibly been largely overlooked to-date. Alternatively, the development of baiting technologies that better attract visually driven animals, or the use of visual lures to attract animals to baits may improve the application of baiting to birds and reptiles (Taggart et al., 2019).

Our results regarding the frequency with which specific species are subject to baiting are broadly consistent with previous studies. For example, in Australia, the red fox is suggested to be the species most frequently subject to control, followed by the European rabbit, wild dog (dingo, domestic dog and hybrids), feral pig, feral goat and domestic cat (Reddiex et al., 2006). Similarly, invasive mammals are said to be the most economically costly animal class in Australia, with domestic cats, rodents, pigs, rabbits and foxes accounting for 95 % of all highly reliable observed cost estimates (Bradshaw et al., 2021). Although neither of these studies focused specifically on the frequency or cost of baiting, our results suggest that the frequency with which these species are managed and their economic costs are approximately consistent with the frequency with which they are subject to baiting (rodents, red fox, rabbit, cat, wild dog/dingo, feral pig, in descending order).

Given that the data collected and recorded by Reddiex et al. (2006) and Bradshaw et al. (2021) documents routine pest animal management operations, the broad consistency in our results also suggests that our study of baiting is generally representative of routine bait applications. However, it is likely that the degree to which our study does represent routine bait application is partially driven by the proportion of a species management that is achieved through baiting. While baiting is the main technique used to manage some species, for example up to 75–85 % of fox and dingo/wild dog control is achieved through baiting, it forms a much smaller proportion of the total management for other species (Reddiex et al., 2006; West and Saunders, 2003).

4.3. How are baiting studies designed?

For many land managers baiting forms part of everyday, routine management. These land managers will typically have limited interest in measuring, quantifying or reporting on baiting outcomes in a robust scientific manner. When put in this context, it can be appreciated why routine pest management operations, with minimal research focus, typically employ poor study design principals (Reddiex and Forsyth, 2006). However, the scientific and grey literature that we summarise here demonstrates that there are many land managers, researchers and practitioners that are interested in measuring, quantifying and reporting on experimental baiting studies. Of these studies, 63 % of bait applications used simple study designs (observational study, after study, before-after study, control-impact study). This is problematic for those that do hold a scientific interest in baiting, as simple designs are known to frequently misrepresent both the magnitude and direction of the true effect following an impact on the population, i.e. a baiting event, relative to more robust designs (before-after-control-impact or random-controlled-trial) (Christie et al., 2019). This high prevalence of simple study designs is additionally concerning for land managers who may not engage in experimental baiting manipulations but do look to apply learnings from the baiting literature to improve their routine management. In some cases, study conclusions or recommendations may misguide land managers or be weakly supported.

Further to poor study design overall, the replication of impact and control sites when baits were applied was low, with a median of 1 impact and 0 control sites per application. Reddiex and Forsyth (2006) argue that this lack of replication in pest control actions may be driven by practical or financial limitations, whereby replication is less practical and more expensive when targeting larger species with larger home ranges. However, our data on baiting was dominated by studies on rodents or other small mammals, with typically small home ranges, and we still recorded limited replication and generally poor baiting design (Pinsky and McCauley, 2019). This suggests that other limitations, such as level of scientific education or understanding, may also be important. While management/study designs with low replication, or few controls can be useful within specific contexts, we encourage practitioners to aim for gold standards (before-after-control-impact or randomised controlled-trial) wherever possible.

4.4. Where does baiting occur?

Baiting occurred in 28 countries worldwide, with the majority (60 %) of bait applications occurring in Australia or New Zealand. Both Australia and New Zealand suffer significant environmental and economic impacts from invasive animals, likely contributing to a strong motivation to conduct lethal baiting (Bradshaw et al., 2021; Goldson et al., 2015). Primary production is additionally a major industry and export commodity for both countries, and an industry within which the lethal control of pest animals is common. Significant impacts on the environment, economy and primary production, and the consequent high motivation to conduct lethal baiting in these countries is further supported by our observation of heavy bias towards the baiting of carnivores in Australia, and both Australia and New Zealand being the leading consumers of sodium monofluoroacetate (Australian Pesticides and Veterinary Medicines Authority, 2008; National Animal Identification and Tracing, 2007; Parlimentary Commissioner for the Environment, 2011).

Nine percent of bait applications occurred across 31 different islands. These were largely for the lethal control of rodents, domestic cats, rabbits, common brushtail possums and brown tree snakes in association with island management or eradication programs. However, the baiting of brown tree snakes only occurred on Guam, United States. Invasive rodents and domestic cats are the greatest threats to island biodiversity and likely responsible for the greatest number of extinctions and ecosystem changes (Campbell et al., 2011; Howald et al., 2007; Nogales et al., 2004). Howald et al. (2007) report rodents to have been eradicated from 284 islands worldwide, with baiting used in over 99 % of eradications; similarly Nogales et al. (2004) and Campbell et al. (2011) report baiting to have been of primary importance in a large proportion of domestic cats eradications worldwide. The results of Howald et al. (2007), Nogales et al. (2004) and Campbell et al. (2011) show that there are many additional island eradications, for which baiting forms a major component, that were not identified by our study, possibly due to going largely or partially unreported, or because they were reported on in the context of island eradications, without focusing on baiting specifically. Regardless, our combined results demonstrate that baiting forms a large and important component of island eradication programs worldwide and is critical to their success, especially the eradication of rodents, cats and rabbits.

The scale of bait applications in our sample varied from 0.0001 to 4000 km^2. While this demonstrates that baiting can and does occur across vast areas, the scale of bait applications appears to be considerably less than the upper scale of pest animal control operations generally, which can reach up to 20,000 km^2 and can involve the application of multiple control tools or methods (Reddiex et al., 2006).

Geographically, omnivores were the most widely targeted animal guild, largely due to the widespread baiting of omnivorous rodents. As demonstrated by the island eradications discussed above, invasive rodents are a major environmental issue worldwide (Howald et al., 2007). Equally, both native and invasive rodents are a common pest species in agricultural crops worldwide, and indeed many instances of rodent baiting in our study were in association with pest management in agricultural crops (Singleton and Petch, 1994; Stenseth et al., 2003). Combined, geographic patterns in baiting appear to highlight patterns in the impacts of pest animals. However, such geographic patterns may also be driven by social, economic or organisational factors that contribute to a practitioner's ability or willingness to conduct baiting or to report on the outcomes of such management. Incorporating studies published in non-English languages into our review may have also altered the observed geographic pattern in baiting (Amano et al., 2021).

4.5. Is baiting a recently emerged wildlife management tool?

Baiting has existed as a tool to manage wildlife populations for centuries. For example, in the mid-1600's sulphur was recommended for the control of moles in Europe, and in Australia the dingo was first baited using arsenic baits in 1814, with their widespread baiting using strychnine closely following (Barker, 1654; Philip, 2019). Similarly, sodium monofluooroacetate was possibly used in baits to poison rats as early as 1904 in Sierra Leone (Wallace, 2014). Despite these early reports of baiting, our data suggest that the reporting of baiting prior to 1960 was infrequent. Bait applications then accelerated considerably in the early 2000's, driven largely by the use of sodium monofluoroacetate (1080). However, sodium monofluoroacetate was available for use in New Zealand from the early 1960's and in Australia in the 1950's, the two largest consumers respectively, and the average volume (kg/ha) of bait dropped aerially in new Zealand peaked in the 1970's (Australian Pesticides and Veterinary Medicines Authority, 2008; National Animal Identification and Tracing, 2007; Parlimentary Commissioner for the Environment, 2011). This likely suggests that the observed increase in bait applications in the early 2000's was associated with an increase in the proportion that were reported on, and not that baiting effort itself increased by an equivalent magnitude.

Seventeen percent of substances and 11 % of species featured in baiting for periods of approximately 35 years or more. However, more than half of substances and species featured in baiting for only a single year. As described above, this suggests that may substances or species feature in bait trials that are not incorporated into routine management and are instead discontinued; diazacon and the baiting of monk parakeets is one example (Avery et al., 2008). Prolonged periods over which the use of certain substances or baiting of certain species have not been reported on may also indicate that for many substances or species, old practices have been discontinued. However, this is not always the case. For example, reporting on baiting can revolve around the development of new products or the targeting of new species, and once methodology is established reporting may become infrequent; alpha-chloralose is currently used routinely in rodenticide baits but reporting on its use has been limited post the 1990's (Fig. 6).

4.6. Knowledge gaps

We noted several knowledge gaps in the baiting literature that warrant attention:

1) Improvement in study designs: A large proportion of studies had simple designs and little or no replication of control or impact sites. While we are the first to report this problem in the baiting literature specifically, we are not the first to report this problem in pest animal management more generally (Hone, 1994; Reddiex and Forsyth, 2006). It is important that we understand why poor management designs dominate this space; if the problem is driven by lack of education or understanding then improvement is possible. Poor management designs also limit opportunities for meta-analysis, and consequently limit opportunities for significant and applied improvements within the baiting and pest management space.
2) Baiting of birds and reptiles: Bird and reptile populations are seldom subject to baiting; despite their populations frequently requiring manipulation for pest management or conservation purposes (Alves et al., 2021; Fessl et al., 2018; Grarock et al., 2014; Krysko et al., 2007; Reed and Rodda, 2009; Rollins et al., 2009). Future work should more thoroughly explore the application of baiting to the management of these taxa.
3) Baiting to achieve non-lethal outcomes: 89 % of bait applications are for the lethal control of a target species. Despite this, baiting can effectively deliver therapeutic substances to target individuals and species; such uses should be further explored and considered, particularly in the context of declining populations of threatened species and increasing wildlife disease outbreaks (Aguirre and Tabor, 2008; Brearley et al., 2013).
4) Improved understanding of population level impacts on non-target species: baiting is a widely used and powerful wildlife management tool. However, we encountered scarce studies that estimate population-level impacts of baiting on non-target species (Fancourt et al., 2022). Most studies reporting non-target impacts describe bait interference or consumption by non-target individuals, or the impact of baiting on a select few, often radio-collared, non-target individuals. Further research focusing on estimating and quantifying population-level impacts to non-target species is required as the results from a select few radio-collared individuals can rarely be extrapolated to the wider non-target population in a robust manner. Such studies are required irrespective of the anticipated extent of population-level non-target impacts.
5) Improved understanding of effort-outcomes relationships for baiting: for some species it has been hypothesised that greater bait densities will result in a greater baiting impact (Ballard et al., 2020). However, for most species such effort-outcomes relationships are poorly described and defined. Better defining such relationships will contribute to achieving optimal impact on the target population at minimal financial and labour costs, but can also contribute to reducing non-target impacts through avoiding the distribution of surplus baits that contribute little to impacts on the target population.
6) Interactions between target and non-target species: when baiting is used to lethally control pest species, lethal non-target impacts on species that would typically predate or compete with the target species may contribute to alleviating top-down pressures on target pest populations or removing key competing species. This could inadvertently promote an environment which is more favourable to the target pest population itself. For example, secondary impacts of rodenticides on key rodent predators may, in the long-term, promote an environment conducive to rodent populations (Lettoof et al., 2020; Lohr and Davis, 2018).
7) Influence of animal learning and cultural transmission of knowledge on baiting efficiency: some studies show that an increase in the resistance of a target population to a specific bait substance is partially responsible for the reduced effectiveness of baiting (Cowan et al., 1995; Twigg et al., 2002). However, animal learning and cultural transmission of knowledge is increasingly being recognised as important in conservation (Brakes et al., 2021; Brakes et al., 2019). For most species it is poorly known to what degree animal learning and cultural transmission of knowledge may contribute to reducing the effectiveness of baiting, despite this having previously been highlighted as a possible barrier to bait effectiveness (Allsop et al., 2017).
8) Consideration of animal movement and space use: baits are often distributed homogenously across areas or along linear transects (tracks/trails). However, animal movement and space use is almost never random (Shaw, 2020). Understanding animal movement within the landscape can lead to more targeted and effective bait deployments that concentrate on focal areas of animal activity (Moseby et al., 2009).

5. Conclusions

1) At least 46 different substances were delivered in baits. The vast majority of baits deliver toxins for the purpose of lethal control, but baiting is also used to deliver therapeutics that benefit target individuals. Sodium monofluoroacetate was the most frequently delivered substance in baits.
2) At least 71 different species were targeted by bait applications; a large majority of these species were mammals. Murids were the most frequently baited family and the red fox was the most frequently baited species.
3) The design of baiting studies was poor and the majority of studies had limited replication of impact and control sites. Most bait applications were conducted by government organisations.
4) Baiting occurred in at least 28 countries worldwide, but over half of all bait applications worldwide occurred in Australia or New Zealand. Approximately one tenth of bait applications occurred on islands. The area over which baits were distributed varied from 0.0001 to 4000 km^2.
5) Reports on baiting drastically increased from the 2000's onwards in association with the use of Sodium monofluoroacetate. Approximately half of substances delivered, and species targeted featured in bait applications for very short periods, comparably few substances delivered and species targeted featured in bait applications for more than three decades.

CRediT authorship contribution statement

P.L.T and K.K·P conceived of the study; all authors contributed to design of study; P.T and P.L.T conducted literature review and extracted data; P.L.T wrote first draft of manuscript; all authors contributed to critically revising manuscript and gave final approval.

Funding

This work was conducted under research funding granted by the Federal Department of Agriculture, Water and the Environment (Activity ID: 4-FY94ZWM).

Declaration of competing interest

The author declare that they have no conflict of interest.

Data availability

Full dataset extracted, along with meta-data, appendices and R code to reproduce results can be found on the Open Science Framework at https://osf.io/wb97u/.

Acknowledgements

Thank you to S McFetridge and T Dorji for input to review planning and discussions. Thank you to S Comte and A Bengsen for providing R code that we adapted to produce our world map and for thoughtful and critical baiting discussions. This work was conducted under research funding granted by the Federal Department of Agriculture, Water and the Environment (Activity ID: 4-FY94ZWM).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biocon.2023.110214.

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