# Preventing extinctions: planning and undertaking invasive rodent eradication from Pinzon Island, Galapagos

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**Abstract** Invasive black rats (*Rattus rattus*) were successfully eradicated during 2012 from Pinzon Island in the Galapagos archipelago using the rodenticide brodifacoum. Potential exposure to brodifacoum in Pinzon tortoises (*Chelonoidis ephippium*), Pinzon lava lizards (*Microlophus duncanensis*) and Galapagos hawks (*Buteo galapagoensis*) was mitigated by captive holding of subpopulations. This was successful for all species during and shortly after baiting, however mortality of Galapagos hawks occurred post-release, likely due to the persistence of residual brodifacoum in lava lizards. Since 2013, Pinzon tortoise hatchlings are surviving in-situ for the first time in at least 120 years and the eradication of black rats is expected to have significant benefits for at least 15 other island-endemic species.

**Keywords:** brodifacoum, endemic species, eradication, *Rattus rattus*, restoration

## INTRODUCTION

Islands are centres of endemism and endangerment, with about one-fifth of the world's threatened amphibians, one-quarter of the threatened mammals and more than one-third of the threatened birds being endemic to islands (Fonseca, et al., 2006). Invasive non-native species are major extinction drivers, with predators like rodents being particularly damaging (Bellard, et al., 2016; Doherty, et al., 2016). Four rodent species (*Rattus rattus, R. norvegicus, R. exulans, Mus musculus*) have been introduced to islands holding 88% of all insular critically endangered or endangered terrestrial vertebrates (TIB Partners, 2014). Invasive rodents cause population declines and extinctions of insular flora and fauna and interrupt ecosystem processes with negative cascading effects (Fukami, et al., 2006; Towns, et al., 2006; Jones, et al., 2008; Kurle, et al., 2008). To recover endangered populations and restore ecosystem processes, invasive rodents on islands are increasingly targeted for eradication, with at least 650 eradication attempts of introduced *Rattus* spp. populations to date (Russell & Holmes, 2015). Eradication of invasive mammals from islands results in positive responses by native species with few exceptions (Jones, et al., 2016).

Pinzon Island (1,815 ha), in the Galapagos archipelago, is uninhabited and is entirely within the Galapagos National Park. Pinzon endemics include three reptiles (Pinzon Island tortoise (*Chelonoidis ephippium*), Pinzon lava lizard (*Microlophus duncanensis*), Pinzon leaf-toed gecko (*Phyllodactylus duncanensis*)), six land snails (*Bulimulus duncanus, B. eschariferus ventrosus, B. pinzonensis, B. pinzonopsis, B. prepinguis, Bulimulus* sp. undescribed), and six insects in the orders Homoptera and Hemiptera. Thirteen species considered threatened by the IUCN are present, such as marine iguanas (*Amblyrhynchus cristatus*), Galápagos hawk (*Buteo galapagoensis*), land snails and the cactus *Opuntia galapageia*, along with several species of unassessed conservation status (IUCN, 2015).

The island was most heavily used by whalers harvesting tortoises in the early to mid-1800s and it is during this period that black rats (*R. rattus*) were most likely introduced, with specimens first collected in 1891 (Patton, et al., 1975). Black rats are the only invasive mammals that successfully populated the island. On visiting Pinzon Island in 1903, Rolland Beck noted "We… captured altogether nearly thirty live tortoises…. We were much chagrined, however, at finding no very small specimens, but soon came to the conclusion that the large rats, of recent introduction, and now common everywhere on the island, eat the young as soon as they are hatched" (Beck, 1903 p. 174). Heavy predation by black rats on eggs and hatchlings saw a halt of recruitment into the tortoise population for over a century, leaving fewer than 65 old tortoises that had survived human harvesting efforts (MacFarland, et al., 1974; Jensen, et al., 2015). In response, a 'head-starting' programme was initiated nearly 50 years ago. This entailed collecting eggs or recently hatched individuals from nests on-island, transporting them to the Galapagos National Park's centre on Santa Cruz Island where hatchlings were reared ex-situ until 4–5 years old, at which time they were repatriated back to Pinzon Island (Jensen, et al., 2015). Elsewhere in the Galapagos Archipelago, invasive black rats have been implicated in the extinction of native rodents, declines and extirpations of sea- and land-bird populations and other fauna (Cruz & Cruz, 1987; Steadman, et al., 1991; Dowler, et al., 2000). By consuming seeds and seedlings they impede vegetation regeneration and alter forest dynamics, affecting entire ecosystems (Clark, 1981). Impacts on invertebrates have not been quantified in the Galapagos Archipelago but likely occur based on reports from elsewhere (e.g. Towns, et al., 2006).

Conservationists attempted to eradicate black rats from Pinzon Island in 1988 utilising rodenticide bait dumps (coumatetralyl powder combined with rice in paper bags) and hand broadcast of baits containing brodifacoum and coumatetralyl (Cayot, et al., 1996; Harper & Carrion, 2011). The project was unsuccessful, although rodents were not detected for nine months after the operation (Cayot, et

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al., 1996). This rodent suppression resulted in recruitment of Pinzon tortoises, anecdotal reports of increases in the abundance of juvenile marine iguanas, populations of Pinzon lava lizards and Galapagos doves (*Zenaida galapagoensis*), and decreases in populations of short-eared owl (*Asio flammeus galapagoensis*) and Galapagos hawks (Muñoz, 1990; Cayot, et al., 1994; Cayot, et al., 1996). A cessation of predation of Pinzon tortoise hatchlings by black rats was recorded, however an 80% predation rate by native Galapagos hawks occurred for two years after the eradication attempt (Morillo Manrique, 1992). Ambitious for its time, this failed eradication attempt set back rodent eradications in the archipelago for the next three decades, with the exception of attempts on just a few small (<20 ha) islands (Harper & Carrion, 2011).

Large-scale feral pig (*Sus scrofa*), goat (*Capra hircus*) and donkey (*Equus asinus*) eradications were implemented in the Galapagos Archipelago throughout the late 1990s and 2000s (Cruz, et al., 2005; Carrion, et al., 2007; Carrion, et al., 2011) renewing interest in large-scale rodent eradications. In 2007, an international workshop laid out a plan for developing capacity and confidence to eventually eradicate rodents from inhabited Floreana Island (17,253 ha) with complexity and scale being increased at each step (CDF & GNPS, 2007). Later in 2007, North Seymour Island (184 ha) was hand baited with wax blocks containing brodifacoum, successfully eradicating black rats (Harper, et al., 2011). In 2011, the first aerial broadcast of brodifacoum baits in South America eradicated rodents from Rabida and 11 other islands totalling 705 ha (Campbell, et al., 2013). Pinzon (1,815 ha) and Plaza Sur (12 ha) islands were originally considered within the group of islands to be targeted along with Rabida but their operations were delayed to allow trials to be conducted for increasing certainty of non-target risks to tortoises and for pilot mitigation strategies for Galapagos hawk (Campbell, et al., 2013). As part of the Rabida project, 20 Galapagos hawks were kept in captivity and released once the risk of mortality from rodenticide poisoning was considered past (Campbell, et al., 2013).

Here we describe the successful eradication of invasive black rats from Pinzon Island and the measures taken to mitigate negative impacts of rodenticide bait application on non-target wildlife.

## METHODS

### Site description

Pinzon Island, located in the centre of the Galapagos Archipelago, has a maximum elevation of 458 m and approximately 18 km of rocky coastline with steep cliffs on the southern and north-western coasts. Large lava blocks dominate the slopes of Pinzon. There are two craters at the centre of the island. The vegetation is xerophytic and there are no permanent bodies of water. Two small islets, each of approximately 0.4 ha in size, lie close inshore. Pinzon has no terrestrial visitor sites and is more than 10 km from any other island with invasive rodents, making unassisted reinvasion highly unlikely.

### Baseline genetic sampling of rodents from Pinzon

In 2011, black rats were trapped, euthanised and samples taken (n=89) for future genetic analyses in case rodents were detected after the eradication attempt. If this occurred, as island populations of black rats can be differentiated in the Galapagos (Willows-Munro, et al., 2016), genetic samples from the pre- and post-eradication attempt could be compared to help determine whether reintroduction or eradication failure occurred (Abdelkrim, et al., 2007).

### Bait application

As with previous rodent eradications in the archipelago, bait application was timed for the last three months of the dry season (October–December), when rat breeding ceases and their numbers are at a minimum, after a typical six-month dry-spell (Clark, 1980). Bait type used was 'Brodifacoum 25D Conservation' (Bell Laboratories, Madison WI). Baits were 2.5 g compacted crushed grain pellets of 13 mm diameter, containing 25 µg (25 ppm) of brodifacoum per kg of bait, blue dye and pyranine biomarker, a non-toxic, odourless and tasteless dye that fluoresces green under UV light. Bait was applied in two aerial applications 23 days apart at an average rate of 6.72 kg/ha for the first application (15–17 November, 2012) and 4.85 kg/ha for the second application (8–9 December, 2012; Fig. 1). Pre-eradication trials in 2010 had determined that target application rates of 6 kg/ha followed by 3 kg/ha ensured bait was available in all habitats for at least four days. It had been planned to have bait applications 7–10

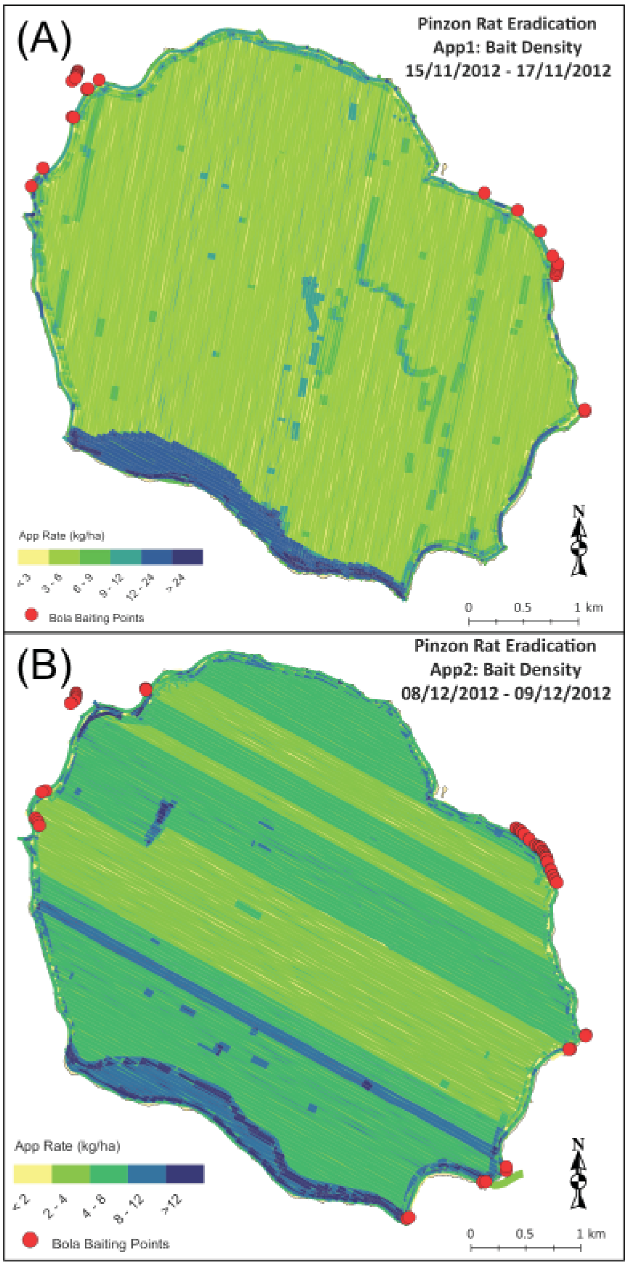


**Fig.1** Bait density (kg/ha) maps of Pinzon Island from (A) first, and (B) second bait applications. Circles indicate where baits in paper bags were applied (bola baiting points).

days apart, however a pregnant rat was reported after the first bait application, prompting a decision to extend the duration between applications to maximise the probability that all rats would be exposed to bait (Keitt, et al., 2015).

An experienced pilot flew the helicopter (Eurocopter AS350-B2, France) guided by GPS, pre-programmed flight lines and light-bar (Tracmap flight unit, New Zealand). The helicopter was fitted with a custom agricultural style bait spreader bucket (CSI Helicopters, New Zealand) that was used to spread bait systematically over Pinzon Island (Fig. 1). Pre-programmed flight-lines 40 m apart provided a 100% overlap for inland areas, as previous bucket calibration indicated the bucket had an 80 m effective baiting swath width. Interior flight-lines ran coast-to-coast, with lines starting and ceasing 40 m inside of the coast to minimise the amount of bait entering the marine environment. Interior flight-lines were flown approximately north–south on the first application and east–west on the second. Two flight-lines were flown around the coast. The 'outer' coastal swath was flown along the coastline with a deflector attached to the bucket, providing 40 m unidirectional sowing towards the inland, to minimise bait entering the ocean. The inner coastal swath was carried out with the standard bucket, 60 m inland from the coast, thereby achieving a 50% overlap with the outer coastal swath. Sections of cliff over 50° slope on the southern side of the island were treated as a separate block to achieve twice the bait application rate of the interior, which is considered best practice (Broome, et al., 2014). GPS tracks were inspected periodically throughout each application. Any gaps identified in bait coverage were then baited in subsequent flights the same day.

Hand-baiting was conducted around the on-island camp, temporary hawk aviaries and one islet. The second islet was baited by hand from the helicopter using paper bags with 10 baits in each to achieve target application rates. Any areas along the coast that may not have received bait due to extreme steepness, overhangs, and deep cut gullies were also hand baited with bait in paper bags. Bait availability plots (25 m × 1 m; n=10) were used to monitor bait persistence after each aerial application at points from the coast to the highlands on the northern side of the island. Plots contained the number of pellets that corresponded to the bait application rate for each application. Each bait pellet was marked with a pin flag, which was removed as pellets were consumed. Plots were checked daily between the first and second applications and for 13 days following the second application.

Two boats acted as a floating base during helicopter baiting operations. One boat, fitted with a helicopter landing platform, also acted as the helicopter refuelling station. The second boat was fitted with a wooden platform from which bait was loaded into the bait spreader bucket as the helicopter hovered to one side.

### Non-target species

Brodifacoum is the most commonly used toxicant for rodent eradications on islands and has the highest success rate (DIISE, 2016). Although an effective rodenticide, brodifacoum is highly toxic to mammals and birds, is known to persist in tissue containing vitamin K epoxide reductase (Eason, et al., 2002) and therefore presents risks to non-target wildlife through primary and secondary pathways of exposure (Broome, et al., 2015). Reptiles are considered to be less susceptible to brodifacoum (Weir, et al., 2015) but may also present a secondary exposure pathway to their predators.

An *a priori* non-target risk assessment which included Pinzon wildlife was conducted in 2010 (Campbell, 2010). A revised assessment (Fisher & Campbell, 2012) incorporated a suite of new information from the 2011 rodent eradications, and captive feeding trials used to assess risk of brodifacoum exposure in giant tortoises, lava lizards, geckos and snakes (Fisher, 2011a; Fisher, 2011b). Lava lizard samples were taken from Rabida Island before and after bait application to assess the incidence and persistence of residual brodifacoum in lava lizards but all these samples perished when a freezer was unplugged. Population-level impacts of brodifacoum applications were assessed for lava lizards and land birds using a before-after control-impact study design on Rabida, Bartolome, Bainbridge #3 and Beagle Sur islands, with Pinzon acting as a control. Based heavily upon the 2012 non-target risk assessment the Galapagos National Park Directorate and other partners determined that mitigation actions should be conducted for Pinzon tortoise, Galapagos hawk, Pinzon lava lizard, lava gull (*Larus fuliginosus*) and endemic land snails. Mitigation plans were developed for each taxon (Cunninghame, 2012; Cunninghame, et al., 2012; Oberg & Campbell, 2012; Parent & Campbell, 2012) except tortoises. Mitigation plans for lava gulls and land snails were not implemented. Lava gulls were not present on Pinzon Island during operations, and in searches undertaken before bait application all snails found were estivating so would not be exposed to bait.

Fifteen adult Pinzon tortoises were brought into captivity two years prior to baiting operations, housed on Santa Cruz Island and returned in good health two years after the rodent eradication was complete. Forty Pinzon lava lizards were taken into captivity prior to baiting and were maintained in enclosures on Pinzon Island. Termite larvae were provided as food every other day. Ten days after the second application the potential for bait consumption by lava lizards, as determined by bait degradation plots, was determined to be minimal and all surviving individuals were released near their capture sites.

Sixty hawks were taken into captivity on Pinzon Island, most prior to baiting operations, held in purpose-built aviaries and maintained on diets of goat meat, day-old chicks and (prior to baiting) rats. All hawks were ringed and genetic samples taken for future study. Four additional hawks were captured, ringed, and treated with injectable (intramuscular) vitamin $K_1$, however due to limited aviary space they were released. Three hawks were identified, but never captured. Captive hawks were released 12–14 days after the second aerial application of bait. Telemetry transmitters were fitted to 32 hawks before release.

### Confirmation of eradication

Efficacy of rat detection methods was demonstrated prior to the eradication. Corrugated plastic chew cards with peanut butter (Oberg, et al., 2014), visual sightings, and signs of activity (prints, faeces, gnawed seed pods) readily indicated rodent presence across Pinzon Island. In January 2015 (25 months after the second bait application), these same methods were used to confirm black rat eradication with 1,140 chew cards deployed for at least 54 days, spaced at 25 m intervals along a trail network covering the island.

## RESULTS

Baiting operations successfully applied bait across the island at the desired rates, as determined by helicopter GPS, baiting rate and effective swath width being overlaid on island maps (Fig. 1). Monitoring conducted more than two years after bait applications did not detect invasive rodents on Pinzon Island. None of the 1,140 chew cards deployed had rodent sign, while nearly 100% of chew cards placed pre-eradication did. Seed pods of *Acacia* spp. were intact and showed no sign of rodent damage across the island.

Based on this evidence we conclude that black rats were eradicated from Pinzon Island.

Bait availability plots indicated that after the first application (6.3 kg/ha) the average remaining density across all plots was above 2 kg/ha until day three (2.07 ± 1.75 kg/ha) and did not drop below 1 kg/ha until day 12 (0.9 ± 1.04 kg/ha). One plot had no bait available on day four; tortoises were observed consuming the baits. When the second application occurred, the average bait density remaining was approximately 0.5 ± 1.14 kg/ha. Bait availability plots for the second application (4.2 ± 1.19 kg/ha), indicated average availability remained above 2 kg/ha until day seven (2.7 ± 1.64 kg/ha), and less than 1 kg/ha remaining at day 12 (0.99 ± 1.67 kg/ha). Individual plots went to zero within two days due to Pinzon tortoises consuming bait.

Consumption of bait by Pinzon lava lizards and Pinzon tortoises was observed at higher rates than anticipated and evidenced by faeces containing blue dye, however no mortality in these species was observed in the wild. Additionally, mitigation efforts were successful at maintaining a separate population of Pinzon lava lizards and Pinzon tortoises as insurance in the case of any unexpected mortality in wild populations. Two lava lizards escaped captivity and five captive lizards died (survival rate of 87%).

All captive Galapagos hawks survived captivity and were released in healthy condition. Between 12 and 170 days after release, mortality of 22 tracked Galapagos hawks was recorded (Rueda, et al., 2016). Necropsy of four of these birds showed signs of anticoagulant toxicosis, with 379 ppb brodifacoum measured in one hawk liver (Rueda, et al., 2016). Monitoring of live-caught Pinzon lava lizards also showed residual brodifacoum in liver, for at least 850 days after bait application (Rueda, et al., 2016). The fate of 28 released hawks remains unknown, but they likely died. The remaining Pinzon Island Galapagos hawk population (n=10) was recaptured, placed into captivity in June 2013 and treated with Vitamin $K_1$, while toxicological monitoring of Pinzon lava lizards continued (Rueda, et al., 2016). These captive Galapagos hawks from Pinzon Island, representing 15% of the original population, were released when risk was considered acceptable in July and August 2016 with telemetry and GPS transmitters. Within three months of release, Galapagos hawks from Pinzon Island had nests with eggs. As of April 2018, nine nesting attempts have resulted in five healthy chicks, two nest failures, one unknown outcome and one pending (P. Castaño, unpublished data 2018). These and related events will be reported in greater detail elsewhere. Galapagos hawks continue to be monitored on Pinzon Island, as does toxicological monitoring in Pinzon lava lizards.

The eradication of black rats and actions taken to mitigate non-target impacts on Pinzon Island cost an estimated $1,501,000 (2013 US dollars). Cost breakdown estimates include planning ($101,000), implementation ($909,000), non-target species management ($101,000) and indirect costs ($390,000) (Holmes, et al., 2015).

## DISCUSSION

Recovery of native and endemic species due to the successful eradication of invasive black rats from Pinzon is already evident, with ongoing monitoring expected to reveal further biodiversity gains. Pinzon tortoise hatchlings are now surviving in the wild for the first time in over 120 years (Tapia Aguilera, et al., 2015). With natural recruitment now occurring the Pinzon tortoise head-starting may soon no longer be required (Jensen, et al., 2015). Land-bird surveys in early 2018 found two species (cactus finch *Geospiza scandens*, Galapagos rail *Laterallus spilonota*) never before recorded from the island (Fessl, et al., unpublished data 2018). Endemic land snails also appear to be on the increase, indeed a new species of land snail was discovered two years post-eradication in permanent snail monitoring plots on the island and is currently being described (C. Parent, unpublished data 2015). With a major threat now removed, threatened land snails and other species may now be eligible for down-listing from the IUCN Red List. Similarly, on Rabida Island, two years after invasive Norway rats (*Rattus norvegicus*) were eradicated, two island endemic land snails that were considered extinct for over 100 years were rediscovered (Campbell, et al., 2013; C. Parent, unpublished data 2012). Also, on Rabida Island, a leaf-toed gecko was found post-eradication in late 2012 (Campbell, et al., 2013). The only known geckos from Rabida were recorded from subfossils estimated at more than 5,700 years old, which were classified to genus only (Steadman, et al., 1991). Although the specimen was identified at the time as the archipelago endemic *Phyllodactylus galapagensis* (W. Tapia Aguilera pers. comm. 2013), a recently proposed taxonomic split divides *P. galapagensis* into four species by major islands, including Pinzon (Torres-Carvajal, et al., 2014). Future analyses including samples of geckos from Rabida Island may also see a unique species identified for that island.

Eradication of black rats from Pinzon Island was arguably a cost-effective conservation action at US$827 / ha, resulting in the removal of a significant threat for at least 15 Pinzon Island endemic species, several archipelago endemic species and 12 IUCN threatened species. The negative impact of this conservation action on Pinzon's population of Galapagos hawks is expected to be short-term, with breeding already underway on the island. However, without additional mitigation actions this population may have been lost due to secondary poisoning, potentially requiring a translocation to re-establish Galapagos hawks on Pinzon Island. Longer-term impacts will only be discovered in time.

The persistence of brodifacoum residues in Pinzon lava lizards for at least 850 days was unexpected (Rueda, et al., 2016) and, as it was unknown at the time, was not considered within *a priori* risk assessments. Ingestion of lizards carrying residual brodifacoum for prolonged periods was likely a significant contributor to unpredicted and unexpectedly high mortality of released Galapagos hawks (Rueda, et al., 2016). The use of a prescribed duration for captive holding was, in hindsight, an error. Future mitigation efforts should use biological criteria (e.g. bait availability, sentinel animals) relevant to the pathways being managed to determine when captive held or translocated non-target species be released after brodifacoum bait has been used for rodent eradication.

Pinzon is currently the largest island in the Galapagos to be freed of invasive rodents, and the fourth-largest island globally to be eradicated of black rats (behind Macquarie, Rangitoto and Australia Islands; DIISE, 2016). Continuing on, as suggested in the original roadmap (CDF & GNPS, 2007), the next island in the Galapagos archipelago being targeted for rodent eradication is Floreana Island, nearly an order of magnitude larger than Pinzon, with 160 human inhabitants, pets, livestock, surface water and a suite of wildlife species that are expected to require mitigation actions (Island Conservation, 2013). Floreana Island represents significant challenges but also major opportunities for incorporating social well-being targets in invasive species eradication projects, as well as biodiversity targets to benefit 55 IUCN threatened species and creating the conditions for the reintroduction of 13 species extirpated by invasive species.

Removing non-native invasive rodents from islands is a proven approach to protecting endemic biodiversity (Jones, et al., 2016), and anticoagulant rodenticides are currently the most reliably effective method to achieve this. Until alternative rodent-specific methods become available (Campbell, et al., 2015), practitioners will have to become increasingly skilled at mitigating risks to non-target species related to rodent eradications to ensure the conservation benefits of this powerful tool are maximised.

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