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Review

Anticoagulant rodenticide use, non-target impacts and regulation: A case study from Australia

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HIGHLIGHTS

- Anticoagulant rodenticides are implicated in non-target wildlife poisoning in Australia.
- No comprehensive monitoring of non-target exposure has been conducted.
- Australia's usage patterns and lax regulations may increase the risk of non-target poisoning.
- Reptiles may be important vectors of rodenticides in Australia and other tropical and arid areas.
- Humans may be at risk of rodenticide exposure when consuming large reptiles.

GRAPHICAL ABSTRACT

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ABSTRACT

The impacts of anticoagulant rodenticides (ARs) on non-target wildlife have been well documented in Europe and North America. While these studies are informative, patterns of non-target poisoning of wildlife elsewhere in the world may differ substantially from patterns occurring in Australia and other countries outside of cool temperate regions due to differences in the types of ARs used, patterns of use, legislation governing sales, and potential pathways of secondary exposure. Most of these differences suggest that the extent and severity of AR poisoning in wildlife may be greater in Australia than elsewhere in the world. While many anecdotal accounts of rodenticide toxicity were found – especially in conjunction with government control efforts and island eradications – no published studies have directly tested rodenticide exposure in non-target Australian wildlife in a comprehensive manner. The effects of private and agricultural use of rodenticides on wildlife have not been adequately assessed. Synthesis of reviewed literature suggests that anticoagulant rodenticides may pose previously unrecognised threats to wildlife and indigenous people in Australia and other nations with diverse and abundant reptile faunas relative to countries with cooler climates where most rodenticide ecotoxicology studies have been conducted. To address the identified knowledge gaps we suggest additional research into the role of reptiles as potential AR vectors, potential novel routes of human exposure, and comprehensive monitoring of rodenticide exposure in Australian wildlife, especially threatened and endangered omnivores and carnivores. Additionally, we recommend regulatory action to harmonise Australian management of ARs with existing and developing global norms.

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Contents

1. Introduction

Anticoagulant rodenticides (ARs) are used worldwide in the management of introduced commensal rodents and their associated threats to crops, infrastructure, and human health (Bradbury, 2008). Baiting with ARs is also the most frequently-used method of eradicating rodents from islands and fenced areas for the purpose of preserving or reintroducing native biodiversity (Hoare and Hare, 2006). These rodenticides function by indirectly blocking recycling of vitamin K, which is a critical component in normal blood clotting in vertebrates (Park et al., 1984). ARs are often divided into first and second generation anticoagulant rodenticides based on when they were first synthesized and differences in chemical structure. Second generation anticoagulant rodenticides (SGARs) generally have higher acute toxicities than first generation anticoagulant rodenticides (FGARs) (Thomas et al., 2011). SGARS are also lethal after a single feed, unlike FGARs which require rodents to feed on them for multiple consecutive days in order to achieve a lethal effect (Erickson and Urban, 2004). During this time, rodents can continue to feed and accumulate higher concentrations of ARs (Bradbury, 2008).

Retention time can vary dramatically between rodenticides but is generally highest in second generation anticoagulant rodenticides. For example, in birds, the United States EPA estimates liver retention times of 35 days for the FGAR warfarin and liver retention times of 248 days and 217 days for the SGARs bromodiolone and brodifacoum, respectively (Erickson and Urban, 2004). This long duration of SGAR persistence in liver tissues allows bioaccumulation and biomagnification in predatory species (Martínez-Padilla et al., 2016). The threat of secondary toxicity is exacerbated by behavioural changes induced in species which directly consume poisoned bait. Pre-lethal effects of ARs include reduced escape response and atypical movement in wood mice (*Apodemus sylvaticus*) and bank voles (*Clethrionomys glareolus*) (Brakes and Smith, 2005) as well as altered activity cycles and a startle response that shifted from bolting to freezing when threatened in brown rats (*Rattus norvegicus*) (Cox and Smith, 1992). Secondary toxicity has been demonstrated in the laboratory in a wide variety of species (reviewed in Joermann, 1998) and toxicity in strict carnivores which are unlikely to eat poisoned bait is well-documented in wild animals (reviewed in Laakso et al., 2010). One study even found anticoagulant rodenticide contamination in four of four mountain lions (*Puma concolor*) sampled, with the deaths of two of the individuals directly attributable to acute anticoagulant intoxication (Riley et al., 2007). Lethal intoxication of an apex predator suggests substantial movement of anticoagulant rodenticides through several trophic levels and is clearly a cause for concern. Consequently, secondary poisoning of wildlife has been identified as a meaningful threat at the population level in several species (Nogeire et al., 2015; Thomas et al., 2011).

The vast majority of both laboratory and field studies of non-target AR poisoning have been conducted in North America, Europe and New Zealand, but few studies have investigated secondary poisoning of wildlife in Australia, where at present, this problem is not widely recognised. The need for additional research into non-target impacts of anticoagulant rodenticides in Australia was identified as early as 1991 and such research was characterised as "required urgently" (Twigg et al., 1991). With some common predatory bird species experiencing unexplained range-wide declines (BirdLife Australia, 2015) and a suite of carnivorous dasyurid marsupials that are already threatened by disease and introduced carnivores (Burbidge and McKenzie, 1989; Woinarski et al., 2015), there is an urgent imperative to understand the role of rodenticide in the decline of susceptible wildlife species in Australia.

2. Aims

The aims of this study are to review the existing evidence for the impacts of anti-coagulant rodenticides on native Australian wildlife and to highlight knowledge gaps and contextualise non-target mortality in Australia relative to other parts of the world where more comprehensive literature exists. We also sought to document the ARs currently used in Australia and to clarify the differences in legislation governing rodenticide use between Australia and a selection of other developed nations. Additionally, we highlight global literature which suggests serious knowledge gaps regarding potentially dangerous impacts of anticoagulant rodenticides on non-target wildlife and indigenous people in Australia and other nations with diverse reptile faunas.

3. Methods

Literature included in this review was obtained by searching Web of Science and Scopus databases for all articles containing the keyword "Australia" in combination with the following keywords: rodenticide, anticoagulant, brodifacoum, bromadiolone, coumatetralyl, difenacoum, diphacinone, difethialone, flocoumafen, pindone, and warfarin. Only articles containing information about the use, wildlife impacts, human exposure and regulation of anticoagulant rodenticides in Australia were retained. References within these papers were searched to locate additional sources of information including PhD theses and government reports. We excluded agricultural bait development trials using baits which did not contain active ingredients, modelling of baiting regimes,

therapeutic use of anticoagulants, lab toxicity trials unrelated to native Australian wildlife, government fact sheets, and other studies that did not directly involve the application of anticoagulant rodenticides or their impacts in Australia. Sources were assigned to seven categories based on their primary topic (Table 1).

In the course of the review, major knowledge gaps relating to interactions between anticoagulant rodenticides and reptiles became apparent. To address these gaps and explore potential impacts in Australia, it was necessary to search world literature relating to reptiles and AR. We followed the same search protocol using the keywords reptile, snake, and lizard in combination with the following keywords: rodenticide, anticoagulant, brodifacoum, bromadiolone, coumatetralyl, difenacoum, diphacinone, difethialone, flocoumafen, pindone, and warfarin. Only literature relating to exposure and impacts of ARs on reptiles was examined. All searches were conducted in December 2017 and January 2018.

4. Results and discussion

4.1. Literature survey

We located a total of 45 publications relating to the use, impacts, and regulation of anticoagulant rodenticides in Australia (Table 1). The most common category of literature included 14 resources comprising 30% of all available publications and related to the documentation of island eradications of rabbits or rodents undertaken for conservation management. While eleven resources related primarily to AR impacts on non-target wildlife, none directly tested rodenticide exposure in a large number of individuals and many were reports of opportunistic observations. One publication, categorised as relating to rodenticide impacts on native wildlife, included only speculative mentions of potential poisoning (Olsen, 1996). Eight resources focused on developing AR-based methods for control of rodents, rabbits and pigs, primarily in agricultural settings. Only five studies related to laboratory testing of toxicity of ARs to non-target Australian wildlife. One tested the toxicity of the FGAR pindone to five Australian bird species (Martin et al., 1994). The other four studies tested toxicity of pindone (Jolly et al., 1994) and the SGAR brodifacoum in brushtail possums (*Trichosurus vulpecula*) (Eason et al., 2017; Littin et al., 2002) and brodifacoum in red-necked wallaby (*Macropus rufogriseus*) (Godfrey, 1984) for the purpose of developing control protocols for these species in New Zealand where they are introduced pests. While toxicity literature from elsewhere in the world is likely to be useful in evaluating the risk of ARs to many Australian taxa, a lack of information on the toxicity of ARs to reptiles and marsupial carnivores prevents meaningful assessment of the potential risks posed to these groups.

4.2. Anticoagulant exposure of non-target wildlife in Australia

We found fifteen sources which described suspected or confirmed cases of anticoagulant rodenticide poisoning in 37 Australian wildlife species (Table 2). Additional cases of poisoning in carnivorous birds held in rehabilitation facilities as a consequence of encountering poisoned rodents while in care have also been reported in a Tasmanian Wedge-tailed Eagle (*Aquila audax fleayi*), a Grey Goshawk (*Accipiter novaehollandiae*), and a Tasmanian Masked Owl (*Tyto novaehollandiae castanops*) (Mooney, 2017) but these records were not included in Table 2 because the poisonings occurred in captivity. Records of wild animal poisonings occurred across the Australian Canberra Territory, the territory of Norfolk Island and all Australian states except for South Australia. One FGAR (pindone) and two SGARs (brodifacoum and bromadiolone) were implicated in the poisonings. Five mammal species, 31 bird species and one reptile species were represented in the records (Table 2). Three species recorded as being poisoned are listed as vulnerable (Boodie (*Bettongia lesueur*), Tasmanian Masked Owl (*Tyto novaehollandiae castanops*), and Northern Giant Petrel (*Macronectes halli*)) and two species are listed as endangered (Norfolk Island Boobooks (*Ninox novaeseelandiae undulata*) and Southern Giant Petrel (*Macronectes giganteus*)). Additionally, another paper raised concern over the role that ARs might play in the decline of the Eastern Quoll (*Dasyurus viverrinus*), a dasyurid marsupial which is listed as endangered (Fancourt, 2016). Further research has been suggested to determine risk levels in this species but no empirical data are available on incidence of secondary toxicity or exposure rates (Fancourt, 2016). Out of the fifteen reports of wildlife poisoning, twelve were definitively related to large deployments of bait by government agencies or broadacre farmers for the purposes of island eradications, agricultural rodent control, or rabbit control (Table 2). Only two of the sources specifically implicated small-scale private use of rodenticides in the poisoning of wildlife (Mooney, 2017; Reece et al., 1985). Such use is largely unregulated and unmonitored and occurs in a large proportion of inhabited locations (Mooney, 2017).

In addition to accounts of wildlife poisoning, we also located published accounts suggesting population-level effects of rodenticide toxicity on carnivorous birds in Australia. Olsen (1996) listed the use of rodenticides in areas of palm cultivation as a potential contributing factor in the decline of Norfolk Island Boobooks (*Ninox novaeseelandiae undulata* × *novaeseelandiae*). Young and Lai (1997) observed a correlation between declines in owl abundance and the use of "Klerat®"a brodifacoum-based rodenticide in sugar cane fields in north Queensland and documented one confirmed and several suspected cases of brodifacoum poisoning in owls (James, 1997). A subsequent report noted three additional cases of owls in Queensland testing positive for brodifacoum residues (0.007 mg/kg, <0.005 mg/kg, and 0.17 mg/kg) in the 1990s and two museum specimens of Southern Boobooks (*Ninox novaeseelandiae*) with rodenticide poisoning listed as their cause of death in the collection notes (Thomas and Kutt, 1997). One of the two specimens, while alive showed symptoms of AR poisoning including "bleeding from the nasal passages; loss of muscle coordination; lethargy including drooping head and eyes; and generally poor and dirty condition" (Thomas and Kutt, 1997). The report reviewed several other factors which could potentially have impacted owl populations in the area and came to the conclusion that there was "significant potential for secondary poisoning of owls to occur in Queensland sugarcane as a result of the use of Klerat®" (Thomas and Kutt, 1997). Crop Care Australia later deregistered Klerat® for use in sugar cane fields over concerns relating to secondary poisoning (Twigg et al., 1999).

An unpublished PhD dissertation examined dynamics of secondary poisoning of avian predators associated with sugar cane fields in Queensland and concluded that the coumatetralyl-based product used to control rats did not pose a threat to predatory birds (Ward, 2008). This conclusion was based largely on the low relative use of canefields for foraging by predatory birds, the low concentration of coumatetralyl in rats captured outside of canefields, and the low toxicity and persistence of coumatetralyl relative to second generation anticoagulant rodenticides (Ward, 2008). Unfortunately, no predatory birds in the treated areas were directly tested for rodenticide exposure. A lack of detection of coumatetralyl in Southern Boobooks in Western Australia as part of an ongoing study supports the low probability of secondary toxicity in raptors.

Table 1
Numbers and categories of publications relating to anticoagulant rodenticides in Australia.

Study type	Number of publications
Island eradications	14
Non-target wildlife impacts	11
Agricultural/feral control trials	8
Captive study	5
Human exposure	4
Pindone reviews	2
Pet exposure	1
Total	45

Table 2
Accounts of non-target AR toxicity in Australian wildlife. *Authors do not specify how poisoning was verified.

Species	Number	Rodenticide	Certainty	State/Territory	Source	Likely Exposure Type	Deitary Category	Reference
Reptiles								
King's skink (*Egernia kingii*)	8	Brodifacoum	Physical symptoms	Western Australia	Island rat eradication	Primary	Omnivore	Bettink, 2015
Birds								
Norfolk Island Boobook (*Ninox novaeseelandiae undulata*)	N/A	Brodifacoum	Suspected	Norfolk Island	Unspecified rat control program	Secondary	Carnivore	Debus, 2012
Straw-necked Ibis (*Threskiornis spinicollis*)	1	Bromadiolone	Physical symptoms	New South Wales	Agricultural mouse control trial	Secondary	Invertivore/carnivore	Saunders, 1983
Barking Owl (*Ninox connivens*)	1	Unknown	Physical symptoms	Queensland	Unknown	Secondary	Carnivore	Thomas and Kutt, 1997
Barn Owl (*Tyto alba*)	1	Brodifacoum	Liver analysis (unknown concentration)	Queensland	Agricultural rat control	Secondary	Carnivore	Thomas and Kutt, 1997
Lesser Sooty Owl (*Tyto multipunctata*)	2	Brodifacoum	Liver analysis (0.007 and < 0.005 mg/kg)	Queensland	Agricultural rat control	Secondary	Carnivore	Thomas and Kutt, 1997
Masked Owl (*Tyto novaehollandiae*)	1	Brodifacoum	Liver analysis (0.17 mg/kg)	Queensland	Agricultural rat control	Secondary	Carnivore	Thomas and Kutt, 1997
Southern Boobook (*Ninox novaeseelandiae*)	1	Unknown	Museum record	Queensland	Unknown	Secondary	Carnivore	Thomas and Kutt, 1997
Brahminy Kite (*Haliastur indus*)	2	Pindone	Suspected	Western Australia	Island rat eradication	Secondary	Carnivore	Martin et al., 1994
Brown Falcon (*Falco berigora*)	1	Unknown	Physical symptoms	Tasmania	Private rodent control	Secondary	Carnivore	Mooney, 2017
Brown Goshawk (*Accipiter fasciatus*)	2	Unknown	Physical symptoms	Tasmania	Private rodent control	Secondary	Carnivore	Mooney, 2017
Collared Sparrowhawk (*Accipiter cirrocephalus*)	1	Unknown	Physical symptoms	Tasmania	Private rodent control	Secondary	Carnivore	Mooney, 2017
Grey Goshawk (*Accipiter novaehollandiae*)	5	Unknown	Physical symptoms	Tasmania	Private rodent control	Secondary	Carnivore	Mooney, 2017
Tasmanian Masked Owl (*Tyto novaehollandiae castanops*)	12	Unknown	Physical symptoms	Tasmania	Private rodent control	Secondary	Carnivore	Mooney, 2017
Tasmanian Boobook (*Ninox novaeseelandiae leucopsis*)	6	Unknown	Physical symptoms	Tasmania	Private rodent control	Secondary	Carnivore	Mooney, 2017
Little Eagle (*Hieraaetus morphnoides*)	N/A	Pindone	Suspected	ACT	Rabbit control	Secondary	Carnivore	Olsen et al., 2013
Wedge-tailed Eagle (*Aquila audax*)	N/A	Pindone	Suspected	ACT	Rabbit control	Secondary	Carnivore	Olsen et al., 2013
Whistling Kite (*Haliastur sphenurus*)	N/A	Pindone	Suspected	ACT	Rabbit control	Secondary	Carnivore	Olsen et al., 2013
Buff-banded Rail (*Gallirallus philippensis*)	5	Brodifacoum	Physical symptoms	Western Australia	Island rat eradication	Primary	Invertivore	Palmer, 2014
Silver Gull (*Larus novaehollandiae*)	7	Brodifacoum	Physical symptoms	Western Australia	Island rat eradication	Both	Invertivore/carnivore	Palmer, 2014
Pacific Golden Plover (*Pluvialis fulva*)	1	Brodifacoum	Suspected	Western Australia	Island rabbit eradication	Both	Invertivore	Palmer, 2014
Ruddy Turnstone (*Arenaria interpres*)	28	Brodifacoum	Physical symptoms	Western Australia	Island rat eradication	Secondary	Invertivore	Palmer, 2014
Buff-banded Rail (*Gallirallus philippensis*)	2	Brodifacoum	Suspected	New South Wales	Island rabbit eradication	Not specified	Omnivore	Priddel et al., 2000
Pied Currawong (*Strepera graculina*)	1	Brodifacoum	Suspected	New South Wales	Island rabbit eradication	Not specified	Omnivore	Priddel et al., 2000
Little Raven (*Corvus mellori*)	1	Bromadiolone	Physical symptoms	Victoria	Residential rodent control	Not specified	Omnivore	Reece et al., 1985
Purple Swamphen (*Porphyrio porphyrio melanotus*)	1	Bromadiolone	Physical symptoms	Victoria	Residential rodent control	Not specified	Omnivore	Reece et al., 1985
Brown Skua (*Stercorarius antarcticus lonnbergi*)	512	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Secondary	Carnivore	Tasmania Parks and Wildlife Service, 2014
Kelp Gull (*Larus dominicus*)	988	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Primary	Invertivore/carnivore	Tasmania Parks and Wildlife Service, 2014
Northern Giant Petrel (*Macronectes giganteus*)	693	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Secondary	Carnivore	Tasmania Parks and Wildlife Service, 2014
Pacific Black Duck (*Anas superciliosa superciliosa*) and Mallard (*A. platyrhynchos platyrhynchos*)	157	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Primary	Omnivore	Tasmania Parks and Wildlife Service, 2014

(continued on next page)

Table 2 (*continued*)

Species	Number	Rodenticide	Certainty	State/Territory	Source	Likely Exposure Type	Deitary Category	Reference
Southern Giant Petrel (*Macronectes halli*)	38	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Secondary	Carnivore	Tasmania Parks and Wildlife Service, 2014
Unknown Bird	5	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Not specified		Tasmania Parks and Wildlife Service, 2014
Unknown giant petrel (*Macronectes* sp.)	31	Brodifacoum	Physical symptoms	Tasmania	Island rabbit eradication	Secondary	Carnivore	Tasmania Parks and Wildlife Service, 2014
Australian Ringneck (*Barnardius zonarius*)	N/A	Pindone	Suspected	Western Australia	Rabbit control	Primary	Herbivore	Twigg et al., 1999
Brahminy Kite (*Haliastur indus*)	N/A	Pindone	Suspected	Western Australia	Rabbit control	Secondary	Carnivore	Twigg et al., 1999
Crested Pigeon (*Ocyphaps lophotes*)	N/A	Pindone	Known*	Western Australia	Rabbit control	primary	Herbivore	Twigg et al., 1999
Grass Owl (*Tyto longimembris*)	1	Brodifacoum	Liver analysis	Queensland	Agricultural rat control	Secondary	Carnivore	Young and Lai, 1997
Masked Owl (*Tyto novaehollandiae*)	1	Brodifacoum	Physical symptoms	Queensland	Agricultural rat control	Secondary	Carnivore	Young and Lai, 1997
Rufous Owl (*Ninox rufa*)	2	Brodifacoum	Physical symptoms	Queensland	Agricultural rat control	Secondary	Carnivore	Young and Lai, 1997
Mammals								
Southern brown bandicoots (*Isoodon obesulus*)	N/A	Pindone	Liver analysis	Western Australia	Rabbit control	Primary	Omnivore	Twigg et al., 1999
Swamp wallaby (*Wallabia bicolor*)	N/A	Pindone	Known*	New South Wales	Rabbit control	Primary	Herbivore	Twigg et al., 1999
Western grey kangaroo (*Macropus fuliginosus*)	N/A	Pindone	Known*	Western Australia	Rabbit control	Primary	Herbivore	Twigg et al., 1999
Brushtail possum (*Trichosurus vulpecula*)	7	Unknown	Physical symptoms	Queensland	Unknown	Not specified	Omnivore	Grillo et al., 2016
Boodie (*Bettongia lesueur*)	20–50	Pindone	Population eradicated	Western Australia	Island rat eradication	Primary	Herbivore	Morris, 2002

Pindone has been implicated as a factor driving the decline of Little Eagle (*Hieraaetus morphnoides*) numbers in and around Canberra (Olsen et al., 2013). Breeding pairs of Little Eagles disappeared from areas baited with pindone while pairs in areas baited with 1080 or not baited at all persisted (Olsen et al., 2013). The high susceptibility of Wedge-tailed Eagles to pindone in laboratory tests (Martin et al., 1994) lends credibility to the hypothesis that pindone could be responsible. Unfortunately, no direct testing of Little Eagles suspected of poisoning was conducted to confirm pindone exposure and rule out other ARs from residential and commercial sources.

Recently, a study in Tasmania examined probable rodenticide poisoning in predatory birds. Six species (Table 2) showed signs of anticoagulant rodenticide poisoning when dissected (Mooney, 2017) but the rodenticides responsible were not determined or quantified. As part of this study, thirteen predatory bird species were ranked by risk of rodenticide exposure according to four natural history parameters: relative metabolic speed, dietary habits influencing consumption of contaminated tissues, relative preference for rodents, and willingness to forage near anthropogenic structures (Mooney, 2017). Development of a more statistically robust predictive model using similar natural history parameters to examine risk of rodenticide exposure in a wider range of predatory species would be an extremely useful step toward assessing likely population level impacts on wildlife in Australia. Incorporating variables relating to seasonal dietary shifts and home range size could potentially improve future models.

The overall lack of attention within Australia to what is perceived as a potentially serious threatening process for native carnivores in many other parts of the world suggests the need for Australian studies which examine potential impacts on native fauna in a quantitative and comprehensive manner. Susceptibility of marsupial carnivores is particularly poorly understood and should be a focus of future research. Furthermore, a surveillance program should be in place in areas of high AR use, to monitor any dead wildlife for a cause of death. Most of the studies we used did not sample animals and thus were not able to confirm suspicions of death due to rodenticide poisoning.

4.3. Governance and legislation of rodenticide use

At present, no information is available on the volume of sales or application of ARs in Australia. Reporting for all poisons intended to control vertebrates indicates that 222 different products are currently registered with a total sales reaching $18,601,875.00 in the 2015–2016 fiscal year (Australian Pesticides and Veterinary Medicines Authority, 2017a). Nine anticoagulants are currently approved for vertebrate pest control in Australia (McLeod and Saunders 2013). At present, all nine are listed as Schedule 6 substances (see Appendix A for schedule meanings) in Australia (Australian Government Department of Health: Therapeutic Goods Administration, 2017) (Table 3) and are legally allowed to be sold directly to the public and do not require government permits for purchase or use. In some cases, more concentrated formulations of SGARs are listed as Schedule 7 substances and are restricted to licensed pesticide applicators (Australian Government Department of Health: Therapeutic Goods Administration, 2017) while products containing low concentrations of some FGARs are registered as schedule 5 substances which require only simple warnings and safety directions for public sale (Table 3). The FGAR diphacinone is currently approved as an active ingredient but has no products registered with the APVMA after July 2016 (Australian Pesticides and Veterinary

Table 3
Anticoagulants currently approved for vertebrate pest control in Australia. Some anticoagulants are assigned different schedules dependant on formulation. *Some disagreement exists as to whether these should be treated as first or second generation anticoagulants †Warfarin is used therapeutically in humans as a blood thinner.

Anticoagulant	Chemical class	Generation	Schedule (See Appendix A)	Acute Oral LD_{50} (*Rattus norvegicus*) mg/kg	LD_{50} Reference	Approved Target Species
Brodifacoum	Hydroxycoumarins	Second	6 (0.25% or less) or 7	0.27	Godfrey, 1985	Mice and rats
Bromadiolone	Hydroxycoumarins	Second	6 (0.25% or less)or 7	0.57–0.75	Meehan, 1978	Mice and rats
Coumatetralyl	Hydroxycoumarins	First	5 (0.05% or less), 6 (1% or less), or 7	16.5	Dubock and Kaukeinen, 1978	Mice and rats
Difenacoum	Hydroxycoumarins	Second	6 (0.25% or less) or 7	1.8–3.5	Bull, 1976	Mice and rats
Difethialone	Hydroxyl-4-benzothiopyranones	Second	6 (0.0025% or less) or 7	0.27–0.69	Lechevin and Poche, 1988	Mice and rats
Diphacinone	Indandiones	First*	6	1.93–2.7	Fisher et al., 2003	Approval expired
Flocoumafen	Hydroxycoumarins	Second	6 (0.005% or less) or 7	0.25–0.56	Lund, 1988	Mice and rats
Pindone	Indandiones	First*	6	75–100	Fisher et al., 2003	Rabbits
Warfarin	Hydroxycoumarins	First	4†, 5 (0.1% or less), or 6	3.3	Fisher et al., 2003	Mice and rats

Medicines Authority, 2017b). However, remaining stock can still be used for 12 months following a stopped registration (Commonwealth of Australia, 1994) and MSDS sheets obtained from a pest management contractor seem to indicate that at least one diphacinone product is still in use at present. The APVMA has prioritised a review of the status of all SGARs currently approved in Australia (brodifacoum, bromadiolone, difenacoum, difethialone, and flocoumafen) citing concerns over public health, worker safety, and environmental safety (Australian Pesticides and Veterinary Medicines Authority, 2015).

Increasing concerns over risks to the health and safety of humans and pets and impacts on non-target wildlife have prompted stricter regulation of anticoagulant rodenticides – particularly SGARs – in several developed nations. While rodenticide legislation is often complex and varies substantially between countries, the trend is toward stricter legislation than currently exists in Australia. In the United States, SGARs are restricted to licensed pesticide applicators, only allowed to be used indoors, and are required to be placed in containers which exclude children and pets (Bradbury, 2008). Similar requirements were subsequently implemented in Canada (Health Canada: Pest Management Regulatory Agency, 2010). A somewhat different approach is taken in the UK, where SGARS are licensed for outdoor use but an industry taskforce has been established to monitor both rodenticide applicator usage patterns and breeding success and SGAR residues in the livers of one sentinel species – Barn Owls (*Tyto alba*) – to determine the impacts of this legislative change on exposure rates (Shore et al., 2016). These alternative models of AR regulation and the direction they represent in evolving global norms should be considered when evaluating current Australian regulations.

Given the changes in legislation governing the use of ARs in other developed nations and demonstrated impacts on human health and wildlife populations overseas, we support the ongoing review of the use and scheduling of SGARs in Australia by the APVMA. In Australia, AR poisoning has been documented in pets (Robertson et al., 1992) and humans (Osborne et al., 2017), particularly children (Ozanne-Smith et al., 2001; Parsons et al., 1996; Reith et al., 2001). Roughly 1400 human exposures to ARs per year are recorded by Poison Information Centres in Australia (Australian Pesticides and Veterinary Medicines Authority, 2015). Removal of SGARs from retail sale to the public by listing all SGARs as schedule 7 poisons and implementing stricter requirements that baits be used only indoors and placed in a manner that makes them inaccessible to children and pets will help to bring Australian practices closer to emerging global norms and best practices. These actions are likely to help to mitigate human health and safety risks and exposure in non-target wildlife. Critical evaluation of whether these practices are effective will require long-term monitoring of AR residues in appropriate sentinel species – as practiced in the UK – before and after any regulatory changes are implemented. Ongoing research into exposure patterns in Southern Boobooks will provide valuable baseline data for a widely-distributed sentinel species if the suggested regulatory changes are implemented.

4.4. Current uses in Australia

4.4.1. Agricultural

In Australian agriculture, ARs are primarily used in asset protection around infrastructure and grain storage areas and many first and second generation products are licensed for these purposes. In the past, several trials have been conducted on broadscale application of rodenticides in Australian cropping systems.

Brown and Singleton (1998) found aerial distribution of brodifacoum-based baits effective at controlling mice in wheat fields in South Australia in a field trial and the authors suggested that application according to guidelines was unlikely to cause substantial non-target mortality. However, mice were observed to be active during the day following the baiting, which the authors acknowledged could increase the risk of secondary poisoning in predatory species (Brown and Singleton, 1998). To our knowledge, aerial distribution of brodifacoum baits in wheat crops has never been implemented on an operational basis in Australian agriculture.

Several trials of bromadiolone efficacy in controlling mouse plagues have been conducted in agricultural crops in Australia. In the earliest of these studies, aerial application was used to distribute bromadiolone bait directly into sunflower crops in New South Wales (Saunders, 1983). Bromadiolone was identified as the most promising of the three toxicants tested but the authors noted concern over bromadiolone's slow method of action potentially facilitating secondary poisoning of predators selecting for poisoned mice (Saunders, 1983). One Straw-necked Ibis (*Threskiornis spinicollis*) was found dead of apparent rodenticide poisoning after having consumed 6–10 mice in an area where bromadiolone had been aerially applied as part of a trial to control mice in sunflower crops (Saunders, 1983). In a subsequent study, wheat laced with bromodialone was applied a single time in bait stations in soybean crops in New South Wales (Twigg et al., 1991). The study did not search for or detect any mortalities in non-target wildlife but cautioned that "The risks to non-target species and of contaminating primary produce posed by broad-scale use of rodenticides would need to be assessed fully before these chemicals could become an integral part of farm management. In Australia, such data are sparse and research is required urgently" (Twigg et al., 1991). The only subsequent available study on broad-scale use of bromadiolone in agriculture used a fertiliser spreader to apply four treatments of wheat laced with bromadiolone to "refuge habitat, channel banks, fence lines, non-arable land and road verges" within 200 m of soybean crops in New South Wales but failed to demonstrate significant reductions in crop damage (Kay et al., 1994). It does not appear that non-target exposure was evaluated as part of this study.

Contrary to the warning issued by Twigg et al. (1991), which cautioned a more complete assessment of non-target impact prior to the broad-scale use of ARs in agriculture, under some circumstances, ARs are or have been used in or adjacent to crops to control mice and rats. During mouse plagues, temporary registrations for the use of bromadiolone have been issued for use in wheat crops in Victoria in 1984, perimeter baiting of oilseed crops in New South Wales in 1984–1985, and in soybean crops in New South Wales in 1989 (Twigg et al., 1991). Expired permits issued to allow the baiting of crop perimeters with bromadiolone show valid periods between 16 September 1999 and 31 December 1999 (PER3031); 06 December 2006 and 30 March 2009 (PER9543); and 31 March 2009 and 30 June 2016 (PER11331) (Australian Pesticides and Veterinary Medicines Authority, 2017b). There are no current permits for the use of bromadiolone in perimeter baiting around crops but a current New South Wales government factsheet and web page state that bromadiolone bait can be prepared by the Livestock Health and Pest Authority (LHPA) for availability to farmers in perimeter baiting around crops (New South Wales Department of Primary Industries, 2011; New South Wales Government: Department of Primary Industries, 2017).

The SGAR brodifacoum was also previously applied broadscale in sugar cane fields in Queensland (Young and Lai, 1997) but the registration for that use has since been revoked over concerns about mortality in non-target wildlife (Twigg et al., 1999). The use of brodifacoum in this context has largely been replaced by the use of the FGAR coumatetralyl. Research on non-target impacts of coumatetralyl in sugar cane fields demonstrated low risk of secondary toxicity (Ward, 2008). Coumatetralyl is currently registered for use in pineapple, macadamia, and sugar cane crops in all states and territories (Australian Pesticides and Veterinary Medicines Authority, 2017b).

Published literature and official accounts may seriously underestimate the usage of ARs in cropping systems in Australia. A study of second generation anticoagulant use in agricultural systems in Northern Ireland found that total compliance with best practice application methods was rare and lack of compliance probably facilitated greater risk of secondary toxicity to native wildlife (Tosh et al., 2011). Within Australia, landowners have requested pindone with the intention of using it to reduce kangaroo abundance in contravention of its label (Twigg et al., 1999). Many ARs are readily available in hardware and agricultural supply stores in Australia without a permit and the potential for use contrary to labelling restrictions is high. A better understanding of current legal and illegal usage of ARs in agriculture is necessary to determine the likelihood of secondary poisoning of non-target species in agricultural systems.

4.4.2. Conservation

ARs have a long history of use on islands and in fenced reserves worldwide for eradication of rodents for conservation purposes. At present, application of ARs is the only effective way of removing introduced rodents from islands larger than 5 ha for conservation purposes (Campbell et al., 2015). Many successful and well-documented eradications of introduced rodents and rabbits have been conducted in Australia using ARs (Bettink, 2015; Burbidge, 2004; Cory et al., 2011; Dunlop et al., 2015; Meek et al., 2011; Morris, 2002; Priddel et al., 2000; Tasmania Parks and Wildlife Service, 2014). Pindone was used in some early eradications but its use has largely been supplanted by brodifacoum (Burbidge and Morris, 2002) and bromadiolone (Meek et al., 2011). Reviews of island eradications have been conducted for New South Wales (Priddel et al., 2011) and Western Australia (Burbidge and Morris, 2002).

During the course of some eradications, high levels of non-target mortality and poisoning of species listed under the Australian *Environment Protection and Biodiversity Conservation Act 1999* have been documented. In one instance, boodies (*Bettongia lesueur*) (listed as vulnerable) were accidentally eradicated on Boodie Island along with the intended target, black rats (*Rattus rattus*) (Morris, 2002). An eradication of black rats was proposed for Woody Island in Western Australia but was halted when the rats on the island were subsequently identified as a native species (*Rattus fuscipes*) (Burbidge et al., 2012). During the successful eradication of rabbits, black rats, and mice (*Mus musculus*) on Macquarie Island, concerns were expressed by the public and government authorities over the observed mortality of 2424 individuals from several seabird and waterfowl species, presumably related to the use of the SGAR brodifacoum (Tasmania Parks and Wildlife Sevice, 2014). While some species, especially Northern Giant Petrels (listed as vulnerable) experienced substantial population-level declines as a result of the baiting, the reductions were expected to be temporary and removal of introduced mammals has already facilitated improved population parameters in a number of seabird species (Tasmania Parks and Wildlife Service, 2014). Endangered Southern Giant Petrels were also lethally poisoned during the course of this eradication (Tasmania Parks and Wildlife Service, 2014). Collateral damage to non-target species may be acceptable and necessary in some situations but more careful consideration and planning are required to avoid poor outcomes which have occurred or been narrowly averted during rodent eradications in the past. In some instances, bait boxes modified to exclude native fauna may decrease the incidence of primary of non-target wildlife AR exposure during eradication attempts (Moro, 2001). Use of biological control agents prior to baiting can also increase the probability of success and reduce the volume of poison needed to remove target animals (Priddel et al., 2000). Close monitoring of non-target mortality during and after island eradications is necessary to properly assess the relative benefit to native biodiversity.

In Australia, ARs have also been tested as a method to control feral pigs for conservation purposes and reduction of agricultural threats. Trials using the FGAR warfarin were conducted in New South Wales (Choquenot et al., 1990; Saunders et al., 1990) and the Australian Capital Territory (McIlroy et al., 1989). While two of the three trials found the use of warfarin to be highly effective, this method does not appear to have been put into practice due to concerns over animal ethics, non-target exposure, and a shift toward the use of 1080 baits for pig control (Cowled et al., 2008). However, the use of warfarin to control feral pigs in Australia has been recommended in the published literature as recently as 2014 (McIlroy, 2014). While warfarin is unlikely to cause secondary poisoning in exposed wildlife, the risk of primary poisoning to wildlife consuming bait intended for pigs is likely too high to warrant the use of this method of control.

4.4.3. Residential and commercial

Patterns of residential and commercial use of ARs in Australia are poorly known. At present, the Australian Pesticide and Veterinary Medicine Association (APVMA) lists seven ARs (two FGARs and five SGARs) as registered for use in Australia in commercial and residential settings (Table 3). We have observed two FGARs (warfarin and coumatetralyl) and three SGARs (brodifacoum, bromadiolone, and difenacoum) available for purchase by the public at retail outlets in Western Australia. The SGARs flocoumafen and difethialone are also used by commercial pest control companies in residential and commercial settings. Residues of both have been detected in native wildlife in Western Australia. Patterns of availability to unlicensed individuals are similar to those in the UK where three FGARs and five SGARs are registered for use and are not restricted to licensed applicators (Shore et al., 2016). However, regulations governing AR use are substantially more restrictive in some other industrialized countries. In the US, three FGARs are permitted for use by the public but all four registered SGARs are restricted to use by licensed pesticide applicators (Bradbury, 2008). Similarly, in Canada the public has access to three FGARs and licensed contractors may use an additional three SGARs (Health Canada: Pest Management Regulatory Agency, 2010).

The lack of available data on the quantities of ARs used in domestic and commercial settings and the locations where they are used makes it nearly impossible to gauge the potential non-target impacts of these

products. Only two publications directly implicate private use of rodenticides in non-target mortality in Australia. In the most definitive example, brodifacoum was implicated in the deaths of a Purple Swamphen (*Porphyrio porphyrio melanotus*) and Little Raven (*Corvus mellori*) which showed signs of AR poisoning after baiting in a residential area (Reece et al., 1985). In Tasmania, residential and small-scale agricultural baiting is thought to have been the source of ARs responsible for the suspected lethal poisonings of 27 individuals from six raptor species (Mooney, 2017). Given that use of rodenticides in conservation and agricultural contexts is relatively limited and only occurs periodically, the total amount deployed in residential and commercial settings is likely to be far greater. Accordingly, overseas studies on rodenticide exposure in bobcats (*Lynx rufus*) in America (Riley et al., 2007) and a variety of bird and mammal species in Spain (López-perea et al., 2015) indicate a spatial correlation between population density and AR exposure in wildlife. Collection of basic information on the quantities of ARs sold to private residents and pest control contractors by locality coupled with systematic testing of wildlife populations across different land-use types will be essential in assessing the risks posed to non-target wildlife by residential and commercial use of ARs.

4.5. Unique considerations in Australia

4.5.1. Pindone

Unlike other ARs used in Australia, the SGAR pindone has received more scrutiny and has been the focus of a greater body of research because of its longer history of use and large scale of use in rabbit control. At present, it is only registered for use in Australia and New Zealand (Fisher et al., 2015; Twigg et al., 1999) and, as a consequence, has received little attention by researchers elsewhere in the world. Efficacy trials for rabbit control were conducted in Western Australia in 1971–1975 (Oliver et al., 1982) and 1981–1982 (Robinson and Wheeler, 1983). Pindone was registered in Western Australia for rabbit control in 1984 and was subsequently registered for the same use in all other Australian states (Twigg et al., 1999). Pindone was registered for use in New Zealand in 1992 (Twigg et al., 1999). In Australia, pindone is used in rabbit control primarily in areas where the use of sodium fluoroacetate (1080) is deemed to pose too great a risk to humans and pets (Department of Agriculture and Food Western Australia, 2015). Such areas include "market gardens, golf courses, hobby farms, around farm buildings" (Twigg et al., 1999) and bushlands adjacent to populated areas. In the past, it has also been used in island eradications of rabbits and rodents prior to being largely replaced by brodifacoum (Burbidge and Morris, 2002; Priddel et al., 2011).

Pindone use in Australia has been the subject of extensive review (National Registration Authority For Agricultural and Veterinary Chemicals, 2002; Twigg et al., 1999) prompted by public concern over reports of lethal poisoning of non-target species (Table 2). As a consequence, additional restrictions were placed on the sale of pindone concentrates and labelling was required to include a "statement not to lay baits in the vicinity of native animal habitat" (National Registration Authority For Agricultural and Veterinary Chemicals, 2002).

At present, little is known about the effects of pindone on non-target species. Pindone has been shown in laboratory tests to have varying effects on different native Australian bird taxa (Martin et al., 1994). Wedge-tailed Eagles were more susceptible than other species tested but Common Bronzewings (*Phaps chalcoptera*) and other granivores were also noted to be at high risk of poisoning due to direct consumption of poisoned grain (Martin et al., 1994). Despite the authors' recommendation for field studies of impacts on Wedge-tailed Eagles and other raptors (Martin et al., 1994), to the best of our knowledge, no further study on this topic has been conducted in Australia.

The repeated use of an anticoagulant in natural areas to control but not eradicate rabbits appears to be unique to Australia and New Zealand. The repeated pattern of use in the same areas may pose a serious long-term threat to susceptible wildlife populations. This may be especially problematic for long-lived species with low reproductive rates which are unable to sustain low levels of additive mortality. The potential link between pindone baiting and the decline of Little Eagles in Canberra (Olsen et al., 2013) exemplifies this concern. However, an ongoing study of rodenticide exposure in Southern Boobooks has not detected any pindone residue in samples tested to date despite testing of samples obtained in areas where pindone baiting has occurred. Differences in diet, territory size, and metabolism could account for this lack of detection. In some instances, reduction of prey abundance via ARs could potentially drive declines in predatory species rather than direct ARs toxicity. However, in the instance of Little Eagles in Canberra, this does not appear to be the case, as the decline of Little Eagle abundance was independent of rabbit abundance (Olsen et al., 2013). Additional research into the sensitivity of Australian fauna to pindone and the population impacts of different patterns of use are necessary to determine the extent and severity of impacts on non-target fauna. At minimum, the continued use of pindone to control rabbits in bushland areas needs to be evaluated as to whether it provides a net benefit or detriment to the conservation of native biodiversity.

Human consumption of rabbits is common in agricultural areas and may facilitate some risk of human exposure to pindone. Risk of substantial human exposure is reduced by the fact that livers are not typically consumed. However, pindone has been demonstrated to accumulate in fat tissue in rabbits at similar concentrations to liver tissue (Fisher et al., 2015). Some discussions of risk of human exposure to ARs via ingestion of contaminated game meats have suggested that cooking prior to consumption might reduce AR exposure through degradation of the relevant chemicals (Eisemann and Swift, 2006). Conversely, subsequent empirical research demonstrated that, at least in pig tissues contaminated with diphacinone, cooking did not substantially reduce AR concentration (Pitt et al., 2011). While we consider the risk of pindone poisoning associated with human consumption of wild rabbits to be low due to its relatively short half-life and low acute toxicity, as a minimum precaution we recommend adhering to established 5 week withholding period for livestock exposed to pindone (Twigg et al., 1999).

4.5.2. Reptiles

We found only one example of documented or suspected lethal AR poisoning of reptiles in Australia (Bettink, 2015) in the course of our literature search. A further investigation of international literature revealed serious gaps in knowledge relating to impacts of ARs on reptiles and their potential role as vectors to higher trophic levels. In combination, the few existing published accounts suggest that some reptiles may be more resistant to anticoagulant rodenticides than birds or mammals. As a consequence, developing a better understanding of how reptiles are impacted by AR exposure and their potential as vectors to more vulnerable taxa will be critical to evaluating the ecotoxicology of ARs in areas of the world where reptiles are a substantial component of biodiversity.

The mechanisms by which carnivorous birds and mammals are exposed to ARs have not been widely researched (Elliott et al., 2014). The few studies investigating AR exposure in intermediate vectors tend to focus on insects (Masuda et al., 2014), and small mammals (Brakes and Smith, 2005) as potential vectors (Elliott et al., 2014) with the vast majority of work focusing on target and non-target small mammals (Hoare and Hare, 2006). Because most of these studies have been conducted in temperate areas of Europe or North America, they may not be representative of dominant exposure pathways in tropical and warm arid areas of the world. In areas where reptiles are more diverse and abundant, reptiles may act as an important pathway for transmission of ARs through terrestrial food webs because of their increased relative importance as prey items for carnivores at higher trophic levels (Hoare and Hare, 2006). Furthermore, in ecosystems with a high predominance of carnivorous reptiles e.g. snakes, monitor lizards and large skinks, there may be a direct bio-accumulation effect when reptiles prey on

rats or mice directly, or on other reptiles, leading to a negative impact on larger-bodied reptiles (Bishop et al., 2016; Olsson et al., 2005).

Reptiles make up a substantial proportion of the prey base of some carnivores in Australia (Doherty et al., 2015; Paltridge, 2002) and comprise >80% of the biomass in the diets of some predatory bird species (Aumann, 2001). Reptile diversity and abundance is substantially higher in Australia than in Europe and North America (Roll et al., 2017) where secondary anticoagulant rodenticide exposure has been more comprehensively assessed in native fauna. As a consequence, understanding patterns of exposure in reptiles and their capacity to transmit ARs to higher trophic levels is critical to understanding ecosystem level AR exposure in Australia and other countries with high reptile abundance. Only a few studies have investigated the mechanisms and ramifications of AR exposure in reptiles (Hoare and Hare, 2006). In one instance, the SGAR brodifacoum was detected in Pinzón lava lizards (*Microlophus duncanensis*) up to 850 days after baiting of an uninhabited island with no other rodenticide sources (Rueda et al., 2016). Long duration of AR persistence in lava lizards could be a consequence of recursive exposure from consumption of invertebrates feeding on reptile faeces containing AR residue, low elimination rates by lizards, or slow decomposition leading to prolonged availability of bait (Rueda et al., 2016). Subsequent deaths of 22 Galapagos hawks (*Buteo galapagoensis*) showing signs of rodenticide toxicity were attributed to secondary poisoning resulting from consumption of lava lizards, as was the death of a short-eared owl (*Asio flammeus*) found dead with lethal concentrations of brodifacoum present in its liver 773 days after baiting (Rueda et al., 2016). If other reptile species are also capable of vectoring lethal levels of rodenticide to higher trophic levels for greater than two years after initial exposure, the threat of secondary poisoning to carnivorous birds and mammals in regions of the world with diverse and abundant herpetofaunas may be severely underestimated.

High tolerance to AR exposure may also increase the efficacy of reptiles as vectors of ARs to higher trophic levels. At least some reptiles appear to be substantially more resistant to AR toxicity than birds or mammals (Weir et al., 2015). An acute oral LD50 of 550 μg/g was determined for the AR pindone in Western fence lizards (*Sceloporus occidentalis*) (Weir et al., 2015). No LD50 was determined for the SGAR brodifacoum because all western fence lizards tested survived the highest does of 1750 μg/g (Weir et al., 2015). Both LD50s are three to five orders of magnitude higher than in most bird and mammals species tested (Laakso et al., 2010). Similarly, when prairie rattlesnakes (*Crotalus viridis*) were fed three laboratory mice poisoned with bromadiolone over the course of three weeks, none of the snakes died or showed signs of rodenticide toxicity in the 30 days following the treatment despite consuming more mg/Kg brodifacoum than the LD50s established for several mammal species in the same study (Poché, 1988). Pitt et al. (2015) examined brodifacoum residues in 112 geckoes (*Lepidodactylus lugubris* and *Hemidactylus frenatus*) collected on Palmyra Atoll after rat control operations. They noted a peak concentration of 0.067 μg/g and detectable concentrations at about half of this rate were still noted 60 days post-baiting (Pitt et al., 2015). Pitt et al. (2015) concluded that geckos were unlikely to experience mortality but on islands where secondary predators existed, there could be some ecosystem-wide impacts. Similarly, bungarras or Gould's goannas (*Varanus gouldii*) were observed consuming rats poisoned with brodifacoum during an eradication in the Montebello Islands of Western Australia, but did not appear to experience adverse effects (Burbidge, 2004). If a tolerance for rodenticides exists across multiple reptile taxa, reptiles may be more effective at concentrating and transmitting ARs to higher trophic levels than the small mammals which have been more commonly examined as potential vectors of ARs to higher trophic levels.

Conversely, in some instances, apparent susceptibility of some reptile species to ARs has been observed or hypothesized. In Australia, the single documented account of lethal AR toxicity in reptiles involved the direct ingestion of brodifacoum baits by King's skinks (*Egernia kingii*) during a rat eradication on Penguin Island in Western Australia (Bettink, 2015). Eight of the skinks were found dead and exhibited haemorrhage associated with AR toxicity and several others were treated with vitamin K and released (Bettink, 2015). Subsequent analysis revealed a concentration of 1.3 mg/kg in the liver of one of the dead skinks (Bettink, 2015). This liver concentration is well above minimum lethal thresholds suggested for many bird and mammal species so it is difficult to infer relative susceptibility of King's skinks from this event. Sánchez-Barbudo et al. (2012) documented the death of a horseshoe whip snake (*Hemmorrhois hippocrepis*) due to flocoumafen used to protect a seabird colony. A number of anecdotal accounts of lethal AR poisoning have also been reported in skinks and geckos (Wedding et al., 2010). Susceptibility of goannas in Australia to poisoning with brodifacoum has also been suggested (James, 1997), although it appears that this only considers the likelihood of exposure due to carrion being a component of their diet rather than an actual vulnerability to the effects of brodifacoum. The lack of observed mortality in some reptile species may be due to a delayed onset of effects relative to birds and mammals. This possibility is supported by the observation of the deaths of six Galápagos land iguanas (*Conolophus subcristatus*) more than two months after their island was baited with brodifacoum to control rats. Merton (1987) described a similar incident in which Telfair's skinks (*Leiolopisma telfairii*) were found dead three to six weeks after AR bait was used on Round Island, Mauritius. The delay in mortality was presumed to be a result of some physiological difference between reptiles and bird and mammals (Merton, 1987). If some reptiles are susceptible to AR poisoning but exhibit substantially delayed mortality, they may be extremely effective vectors to vulnerable species in higher trophic levels if they are able to ingest higher levels of rodenticide over the pre-lethal period and if mortality is preceded by behaviours which increase the likelihood of predation. Laboratory toxicity tests are needed across a representative suite of reptile taxa to resolve questions around the dangers posed to reptiles by ARs and the capacity of reptiles to vector ARs to higher trophic levels. Extensive testing of wild reptiles would be useful in assessing exposure rates and ecological impacts of reptile exposure to ARs.

Primary consumption of ARs by reptiles through direct consumption of baits intended for rodents also requires additional evaluation as a source of AR contamination in terrestrial ecosystems. In captive trials, some but not all skinks (*Oligosoma maccanni*) consumed or licked pindone bait, with increased consumption when the bait was wet (Freeman et al., 1996). Direct consumption of brodifacoum baits by Shore Skinks (*Oligosoma smithi*) in the wild has been observed in New Zealand (Wedding et al., 2010). Wedding et al. (2010) cite records of five other skink species eating cereal baits, some of which contained rodenticides. Bennison et al., 2016 used dye tracers to prove that the large carnivorous King's Skink (*Egernia kingii*) had ingested non-toxic baits laid out on islands off the West Australian coast. King's Skinks were subsequently observed consuming baits containing brodifacoum during the course of a rat eradication on Penguin Island in Western Australia, despite the use of specially designed bait containers intended to exclude the skinks (Bettink, 2015). Others have observed bobtails (*Tiliqua rugosa*) – another large omnivorous skink – inside AR bait boxes in urban areas (Ashleigh Wolfe, Personal communication).

These examples are cause for concern, as both bobtails and large skinks in the genus *Egernia* have been documented as prey remains at Wedge-tailed Eagle (*Aquila audax*) nests across a large geographic area (Brooker and Ridpath, 1980). In one instance, remains of 13 bobtails were found below a Wedge-tailed Eagle nest on a single visit (Simon Cherriman, unpublished data). Wedge-tailed Eagles are important top carnivores in Australian food webs and are highly susceptible to toxicity from the anticoagulant rodenticide pindone relative to other bird species tested (Martin et al., 1994). Other carnivorous birds and mammals with a higher proportion of reptiles in their diet could potentially be at greater risk.

Reptiles could also potentially serve as an effective vector of ARs between invertebrates which consume baits and more sensitive vertebrates at higher trophic levels. Invertebrates have been implicated in directly vectoring rodenticides to bird species including New Zealand Dotterels (*Charadrius obscurus aquilonius*) (Dowding et al., 2006) and nestling Stewart Island robins (*Petroica australis rakiura*) (Masuda et al., 2014) as well as the insectivorous European hedgehog (*Erinaceus europaeus*) (Dowding et al., 2010). If the relative tolerance of ARs demonstrated by Weir et al. (2015) is consistent across numerous reptile taxa, the potential for reptiles to bioaccumulate and biomagnify ARs from lower trophic levels and subsequently retain them for long periods of time makes insectivorous reptiles a potentially important and widely unrecognised vector for anticoagulant rodenticides to more susceptible fauna in higher trophic levels.

In Australia, some reptile species, particularly goannas (*Varanus* spp.), are a culturally and economically important component of a traditional diet for some indigenous peoples (Scelza et al., 2017). Liver tissue of varanids is consumed by some indigenous groups (Caroline Long, Personal communication) and fatty tissues of monitor lizards are eaten preferentially to other body parts (Gracey, 2000). Some rodenticides are known to accumulate to high levels in fat tissue in mammals (Fisher et al., 2015) but accumulation patterns in reptiles are unknown. During the course of a rodent eradication on islands in Western Australia, bungaras (*Varanus gouldii*) were "observed eating dead and dying rats to the extent that some droppings contained the green dye from the bait" which contained brodifacoum but no mortalities were observed (Burbidge, 2004). These observations raise concerns that if baiting has occurred in or near areas where traditional hunting of varanids takes place, the consumption of varanid tissues likely to accumulate ARs may present a previously unrecognised human health and safety risk. Consumption of feral cats by indigenous people may pose another pathway for rodenticide exposure, as feral cats have been killed by secondary AR poisoning during baiting events in New Zealand (Alterio, 1996). Several studies have cautioned against the consumption of wild game in areas where ARs have been used (Eisemann and Swift, 2006; Pitt et al., 2011), particularly SGARs (Eason et al., 2001). The risks posed by consumption of varanids may be substantially greater than risks associated with rabbit consumption for several reasons. Unlike rabbits which are targeted in discrete baiting events with a FGAR for which there is an established withholding period, varanids are not exposed in a predictable manner and may be chronically exposed to stronger and more persistent SGARs with no established withholding period. The presumed greater physiological tolerance of varanids to ARs and the regular consumption of varanid livers as part of traditional practices considerably elevate the risks associated with varanid consumption relative to rabbit consumption. Urgent investigation of potential rodenticide accumulation in varanids is needed but should take into consideration the high value of this taxon as a traditional food source and the cultural importance of traditional hunting practices. Use of wild reptiles as a food resource is most common in tropical and subtropical areas of the world (Klemens and Thorbjarnarson, 1995) where the prevalence of ARs in wildlife has not been well-studied.

The limited literature available suggests that some reptile species are capable of direct bait consumption, long AR retention time, and a capacity to tolerate and biomagnify high concentrations of potent SGARs. These attributes potentially greatly increase the risk of secondary and tertiary vectoring of ARs to more susceptible bird and mammal species in higher trophic levels relative to other regions of the world where small mammals are believed to be the primary vectors. Additional research into the prevalence of AR exposure across a representative sample of reptile taxa will be critical to evaluating the threat of secondary AR poisoning to wildlife in Australia and other countries with high abundance and diversity of reptiles. Depending on the severity and extent of exposure detected, additional work may be warranted to investigate the pathways driving this exposure and the role that reptiles play in vectoring rodenticides to animals in higher trophic levels including humans.

5. Conclusions and recommendations

Most research on exposure of non-target wildlife to ARs has been conducted in cool temperate regions, particularly in North America, Europe, and New Zealand. Patterns of exposure detected in these studies may differ from those in Australia and other tropical and warm arid countries due to differences in the specific ARs used, regulations governing use, and fundamental differences in the taxonomic composition and susceptibility of native fauna. A better understanding of existing knowledge gaps will facilitate more effective and scientifically-informed mitigation measures in Australia and countries with similar climates.

In Australia, individuals from 37 species across different feeding guilds, trophic levels, and taxonomic groups have tested positive for AR exposure or are suspected to have been lethally poisoned but most documentation is anecdotal or opportunistic in nature. Instances of poisoning were documented across a wide range of geographic areas but spatial patterns of AR exposure are poorly understood. To date, no thorough investigations directly testing for AR exposure in Australian wildlife have been conducted. Island eradications, feral rabbit control, agricultural application, and residential use have all been implicated as sources of ARs which caused non-target wildlife mortality but the relative contributions of these sources have not been quantified.

In aggregate, what little research exists on the interaction between reptiles and ARs, suggests that at least some reptile species may be relatively resistant to the effects but likely to be exposed at high levels. Physiological tolerance, coupled with long retention times could make reptiles effective vectors of ARs in areas of the world where reptiles are abundant. Understanding these dynamics will be critical to understanding the ecology of ARs in tropical and warm arid climates where impacts on wildlife are largely unknown. Effective vectoring of ARs by reptiles poses a potential unevaluated risk to human health in areas where wild reptiles are harvested for human consumption.

At present, Australia's regulatory framework governing the use of ARs is not consistent with emerging practices in other industrialized nations. Restricting SGARs to licensed users and indoor use will likely reduce the incidence and severity of non-target poisoning and the use of lockable bait boxes could reduce risks to children and pets. Coupling these proposed changes with targeted monitoring of rodenticide residues in selected sentinel species will be important in evaluating the efficacy of regulatory changes at reducing non-target mortality. In areas where rodents have developed resistance to FGARs, use of other classes of rodenticides with lower risk of bioaccumulation (such as cholecalciferol) may be a viable option for rodent control with substantially reduced risk of secondary toxicity. At minimum, greater public availability of information on the types, quantities, and locations of ARs sold is necessary to evaluate the risks they pose to non-target wildlife and humans.

To address identified knowledge gaps, we suggest the following research priorities:

- Development of species-specific exposure risk models for carnivorous and omnivorous fauna based on life history parameters
- Systematic nation-wide testing of multiple taxa of carnivorous and omnivorous wildlife for AR exposure, especially:
  - species of conservation concern
  - species consuming small mammals and carrion
  - marsupial carnivores and scavengers
  - reptile carnivores and scavengers
- Systematic long-term testing of geographically widespread and common sentinel species to detect temporal and spatial patterns in AR prevalence

- Evaluation of the relative contributions of residential, commercial and agricultural use of ARs to wildlife poisoning in Australia
  - Examine incidence of non-compliance with existing legislation governing AR use
  - Collection and evaluation of data relating to AR sales and application in Australia

- Evaluation of the net impact on biodiversity of the use of pindone in and around bushland areas
- Captive testing of the sensitivity of a wider suite of wildlife species, especially marsupial carnivores and reptiles to SGARs and pindone
- Examination of the role of reptiles as a vector for ARs in tropical and subtropical nations
- Evaluation of the risk of rodenticide exposure in humans consuming wild reptiles

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Appendix A. Definitions of Schedules applying to all Anticoagulant Rodenticides Registered in Australia from (Australian Government Department of Health: Therapeutic Goods Administration, 2017)

Schedule 4. – Prescription Only Medicine, or Prescription Animal Remedy – Substances, the use or supply of which should be by or on the order of persons permitted by State or Territory legislation to prescribe and should be available from a pharmacist on prescription.

Schedule 5. – Caution – Substances with a low potential for causing harm, the extent of which can be reduced through the use of appropriate packaging with simple warnings and safety directions on the label.

Schedule 6. – Poison – Substances with a moderate potential for causing harm, the extent of which can be reduced through the use of distinctive packaging with strong warnings and safety directions on the label.

Schedule 7. – Dangerous Poison – Substances with a high potential for causing harm at low exposure and which require special precautions during manufacture, handling or use. These poisons should be available only to specialised or authorised users who have the skills necessary to handle them safely. Special regulations restricting their availability, possession, storage or use may apply.

References

Alterio, N., 1996. Secondary poisoning of stoats (*Mustela erminea*), feral ferrets (*Mustela furo*), and feral house cats (*Felis catus*) by the anticoagulant poison, brodifacoum. N. Z. J. Zool. 23:331–338. https://doi.org/10.1080/03014223.1996.9518092.

Aumann, T., 2001. An intraspecific and interspecific comparison of raptor diets in the south-west of the Northern Territory, Australia. Wildl. Res. 28, 379–393.

Australian Government Department of Health, 2017. Therapeutic Goods Administration. The Poisons Standard June 2017. Canberra.

Australian Pesticides and Veterinary Medicines Authority, 2015. Second generation anticoagulant rodenticides—priority 2 [WWW Document]. https://apvma.gov.au/node/19286, Accessed date: 14 July 2017.

Australian Pesticides and Veterinary Medicines Authority, 2017a. Commonwealth of Australia Gazette: Agricultural and Veterinary Chemicals. Vol. 6 p. 18.

Australian Pesticides and Veterinary Medicines Authority, 2017b. Agricultural and Veterinary Permits Search [WWW Document]. https://portal.apvma.gov.au/permits?p_auth=MpDv1rrW&p_p_id=permitsportlet_WAR_permitsportlet&p_p_lifecycle=1&p_p_state=normal&p_p_mode=view&p_p_col_id=column-1&p_p_col_pos=1&p_p_col_count=3&_permitsportlet_WAR_permitsportlet_javax.portlet.action=search, Accessed date: 4 August 2017.

Bennison, C., Friend, J.A., Button, T., Mills, H., Lambert, C., Bencini, R., 2016. Potential impacts of poison baiting for introduced house mice on native animals on islands in Jurien Bay, Western Australia. Wildl. Res. 43, 61–68.

Bettink, K., 2015. Control and Eradication of Black Rats (*Rattus rattus*) on Penguin Island, Western Australia, December 2012 – December 2014. Perth, Western Australia.

BirdLife Australia, 2015. The State of Australia's Birds 2015. Melbourne.

Bishop, C.A., Williams, K.E., Kirk, D.A., Nantel, P., Reed, E., Elliott, J.E., Kirk, D.A., Reed, E., Elliott, J.E., 2016. A population model of the impact of a rodenticide containing strychnine on Great Basin Gopher snakes (*Pituophis catenifer* deserticola). Ecotoxicology 25: 1390–1405. https://doi.org/10.1007/s10646-016-1690-2.

Bradbury, S., 2008. Risk Mitigation Decision for Ten Rodenticides. Washington D.C., USA.

Brakes, C.R., Smith, R.H., 2005. Exposure of non-target small mammals to rodenticides: short-term effects, recovery and implications for secondary poisoning. J. Appl. Ecol. 42:118–128. https://doi.org/10.1111/j.1365-2664.2005.00997.x.

Brooker, M.G., Ridpath, M.G., 1980. The diet of the wedge-tailed eagle, Aquila Audax, in Western Australia. Aust. Wildl. Res. 7:433–452. https://doi.org/10.1071/WR9800433.

Brown, P.R., Singleton, G.R., 1998. Efficacy of brodifacoum to control house mice, *Mus domesticus*, in wheat crops in Southern Australia. Crop Prot. 17:345–352. https://doi.org/10.1016/S0261-2194(98)00026-X.

Bull, J.O., 1976. Laboratory and field investigations with difenacoum, a promising new rodenticide. Proceedings of the Vertebrate Pest Conference, pp. 72–84.

Burbidge, A.A., 2004. Montebello renewal: western shield review — February 2003. Conserv. Sci. West. Aust. 5, 194–201.

Burbidge, A.A., McKenzie, N.L., 1989. Patterns in the modern decline of Western Australia's vertebrate fauna: causes and conservation implications. Biol. Conserv. 50, 143–198.

Burbidge, A.A., Morris, K.D., 2002. Introduced mammal eradications for nature conservation on Western Australian islands: a review. In: Veitch, C.R., Clout, M.N., Towns, D.R. (Eds.), Turning the Tide: The Eradication of Invasive Species. IUCN SSC Invasive Species Specialist Group, Gland, Switzerland, pp. 64–70.

Burbidge, A.A., Abbott, I., Comer, S., Adams, E., Berry, O., Penwarden, K.E., 2012. Unforeseen consequences of a misidentified rodent: case study from the Archipelago of the Recherche, Western Australia. Aust. Mammal. 34:55–58. https://doi.org/10.1071/AM11004.

Campbell, K.J., Beek, J., Eason, C.T., Glen, A.S., Godwin, J., Gould, F., Holmes, N.D., Howald, G.R., Madden, F.M., Ponder, J.B., Threadgill, D.W., Wegmann, A.S., Baxter, G.S., 2015. The next generation of rodent eradications: innovative technologies and tools to improve species specificity and increase their feasibility on islands. Biol. Conserv. 185: 47–58. https://doi.org/10.1016/j.biocon.2014.10.016.

Choquenot, D., Barry, K., Lukins, B., 1990. An evaluation of warfarin for the control of feral pigs. J. Wildl. Manag. 54, 353–359.

Commonwealth of Australia, 1994. Agricultural and Veterinary Chemicals Code Act 1994. Australia.

Cory, F., Wilson, A., Priddel, D., Carlile, N., Klomp, N., 2011. Eradication of the House Mouse (*Mus musculus*) from Montague Island, New South Wales, Australia. Ecol. Manag. Restor. 12:102–109. https://doi.org/10.1111/j.1442-8903.2011.00583.x.

Cowled, B.D., Elsworth, P., Lapidge, S.J., 2008. Additional toxins for feral pig (*Sus scrofa*) control: identifying and testing Achilles' heels. Wildl. Res. 35:651–662. https://doi.org/10.1071/WR07072.

Cox, P., Smith, R.H., 1992. Rodenticide ecotoxicology: pre-lethal effects of anticoagulants on rat behaviour. Vertebrate Pest Conference Proceedings Collection. Lincoln, Nebraska, pp. 165–170.

Debus, S.J.S., 2012. Norfolk Island Boobook chick deaths. Boobook 30, 6.

Department of Agriculture and Food Western Australia, 2015. Rabbit control: bait products [WWW Document]. https://www.agric.wa.gov.au/1080/rabbit-control-bait-products?page=0,2, Accessed date: 15 June 2015.

Doherty, T.S., Davis, R.A., van Etten, E.J.B., Algar, D., Collier, N., Dickman, C.R., Edwards, G., Masters, P., Palmer, R., Robinson, S., 2015. A continental-scale analysis of feral cat diet in Australia. J. Biogeogr. 42:964–975. https://doi.org/10.1111/jbi.12469.

Dowding, J.E., Lovegrove, T. im G., Kast, S.N., Puckett, M., 2006. Mortality of northern New Zealand dotterels (*Charadrius obscurus* aquilonius) following an aerial poisoning operation. Notornis 53, 235–239.

Dowding, C.V., Shore, R.F., Worgan, A., Baker, P.J., Harris, S., 2010. Accumulation of anticoagulant rodenticides in a non-target insectivore, the European hedgehog (*Erinaceus europaeus*). Environ. Pollut. 158, 161–166.

Dubock, A.C., Kaukeinen, D.E., 1978. Brodifacoum (TALON™ RODENTICIDE), A novel concept. Proceedings of the Vertebrate Pest Conference, pp. 127–137.

Dunlop, J.N., Rippey, E., Bradshaw, L.E., Burbidge, A.A., 2015. Recovery of seabird colonies on Rat Island (Houtman Abrolhos) following the eradication of introduced predators. J. R. Soc. West. Aust. 98, 29–36.

Eason, C.T., Wright, G.R.G., Milne, L.M., Morriss, G.A., 2001. Laboratory and field studies of brodifacoum residues in relation to risk of exposure to wildlife and people. Sci. Conserv. 177, 11–23.

Eason, C.T., Wright, G.R., Batcheler, D., 2017. Anticoagulant effects and the persistence of brodifacoum in possums (*Trichosurus vulpecula*). N. Z. J. Agric. Res. 39:397–400. https://doi.org/10.1080/00288233.1996.9513199.

Eisemann, J.D., Swift, C.E., 2006. Ecological and human health hazards from broadcast application of 0.005% diphacinone RODENTICIDE BAITS in Native Hawaiian Ecosystems. In: Timm, R.M., O'Brien, J.M. (Eds.), Proceedings of the Vertebrate Pest Conference. University of California, Davis, California, pp. 413–433.

Elliott, J.E., Hindmarch, S., Albert, C.A., Emery, J., Mineau, P., Maisonneuve, F., 2014. Exposure pathways of anticoagulant rodenticides to nontarget wildlife. Environ. Monit. Assess. 186:895–906. https://doi.org/10.1007/s10661-013-3422-x.

Erickson, W., Urban, D., 2004. Potential Risk of Nine Rodenticides to Birds and Mammals: A Comparative Approach. Washington DC.

Fancourt, B.A., 2016. Diagnosing species decline: a contextual review of threats, causes and future directions for management and conservation of the eastern quoll. Wildl. Res. 43, 197–211.

Fisher, P., O'Connor, C., Wright, G., Eason, C.T., 2003. Persistence of four Anticoagulant Rodenticides in the Livers of Laboratory Rats. DOC Science Internal Series, Wellington, New Zealand.

Fisher, P., Brown, S., Arrow, J., 2015. Pindone residues in rabbit tissues: implications for secondary hazard and risk to non-target wildlife. Wildl. Res. 42, 362–370.

Freeman, A.B., Hickling, J.G., Bannock, C.A., 1996. Response of the skink *Oligosoma maccanni* (Reptilia: Lacertilia) to two vertebrate pest- control baits. Wildl. Res. 23: 511–516. https://doi.org/10.1071/WR9960511.

Godfrey, M.E.R., 1984. Acute toxicity of brodifacoum to wallabies (*Macropus rufogriseus*). N. Z. J. Exp. Agric. 12:63–64. https://doi.org/10.1080/03015521.1984.10427791.

Godfrey, M.E.R., 1985. Non-target and secondary poisoning hazards of "second generation" anticoagulants. Acta Zool. Fenn. 173, 209–212.

Gracey, M., 2000. Historical, cultural, political, and social influences on dietary patterns and nutrition in Australian Aboriginal children 1–4. Am. J. Clin. Nutr. 72, 1361–1367.

Grillo, T., Cox-Witton, K., Gilchrist, S., Ban, S., 2016. Suspected rodenticide poisoning in possums. Anim. Heal. Surveill. Q. 21, 8.

Health Canada, 2010. Pest management regulatory agency. Risk Mitigation Measures for Eight Rodenticides.

Hoare, J.M., Hare, K.M., 2006. The impact of brodifacoum on non-target wildlife: gaps in knowledge. N. Z. J. Ecol. 30, 157–167.

James, D., 1997. Rat-baiting in cane fields & poisoning of wildlife. Boobook 18, 5.

Joermann, G., 1998. A review of secondary-poisoning studies with rodenticides. OEPP/EPPO Bull. 28:157–176. https://doi.org/10.1111/j.1365-2338.1998.tb00717.x.

Jolly, S.E., Eason, C.T., Frampton, C., Gumbrell, R.C., 1994. The anticoagulant pindone causes liver damage in the brushtail possum (*Trichosurus vulpecula*). Aust. Vet. J. 71, 220.

Kay, B.J., Twigg, L.E., Nicol, H.I., 1994. The strategic use of rodenticides against house mice (*Mus domesticus*) prior to crop invasion. Wildl. Res. 11–19.

Klemens, M.W., Thorbjarnarson, J.B., 1995. Reptiles as a food resource. Biodivers. Conserv. 4, 281–298.

Laakso, S., Suomalainen, K., Koivisto, S., 2010. Literature Review on Residues of Anticoagulant Rodenticides in Nontarget Animals. Copenhagen.

Lechevin, J.C., Poche, R.M., 1988. Activity OF LM 2219 (Difethialone), a new anticoagulant rodenticide. Commensal Rodents, in: Proceedings of the Vertebrate Pest Conference. University of California, Davis, pp. 59–63.

Littin, K.E., O'Connor, C.E., Gregory, N.G., Mellor, D.J., Eason, C.T., 2002. Behaviour, coagulopathy and pathology of brushtail possums (*Trichosurus vulpecula*) poisoned with brodifacoum. Wildl. Res. 29, 259–267.

López-perea, J.J., Camarero, P.R., Molina-lópez, R.A., Parpal, L., Obón, E., Solá, J., Mateo, R., 2015. Interspecific and geographical differences in anticoagulant rodenticide residues of predatory wildlife from the Mediterranean region of Spain. Sci. Total Environ. 511: 259–267. https://doi.org/10.1016/j.scitotenv.2014.12.042.

Lund, M., 1988. Flocoumafen – a New Anticoagulant Rodenticide. In: Crabb, A.C., Marsh, R.E. (Eds.), Proceedings of the Vertebrate Pest Conference. Davis, California, pp. 53–58.

Martin, G.R., Kirkpatrick, W., King, D., Robertson, I., Hood, P., Sutherland, J., 1994. Assessment of the potential toxicity of an anticoagulant, pindone (2-Pivalyl-1,3-Indandione), to some Australian birds. Wildl. Res. 21:85–93. https://doi.org/10.1071/WR9940085.

Martínez-Padilla, J., López-Idiáquez, D., López-Perea, J.J., Mateo, R., Paz, A., Viñuela, J., 2016. A negative association between bromadiolone exposure and nestling body condition in common kestrels: management implications for vole outbreaks. Pest Manag. Sci. 73:364–370. https://doi.org/10.1002/ps.4435.

Masuda, B.M., Fisher, P., Jamieson, I.G., 2014. Anticoagulant rodenticide brodifacoum detected in dead nestlings of an insectivorous passerine. N. Z. J. Ecol. 38, 110–115.

McIlroy, J.C., 2014. New techniques for an old problem-recent advances in feral pig control in Australia. J. Mt. Ecol. 3, 241–244.

McIlroy, J.C., Braysher, M., Saunders, G.R., 1989. Effectiveness of a warfarin-poisoning campaign against feral pigs, Sus scrofa, in Namadgi National Park, A.C.T. Aust. Wildl. Res. 16:195–202. https://doi.org/10.1071/WR9890195.

McLeod, L., Saunders, G., 2013. Pesticides used in the Management of Vertebrate Pests in Australia : A Review. New South Wales Department of Primary Industries, Orange, NSW.

Meehan, A.P., 1978. Rodenticidal activity of bromadiolone — a new anticoagulant. Proceedings of the Vertebrate Pest Conference, pp. 122–126.

Meek, P.D., Hawksby, R.J., Ardler, A., Hudson, M., Tuckey, K.D., 2011. Eradication of black rats *Rattus rattus* L. from Bowen Island, Jervis Bay NSW. Aust. Zool. 35, 560–568.

Merton, D.V., 1987. Eradication of rabbits from Round Island, Mauritius: a conservation success story. Dodo 24, 19–24.

Mooney, N., 2017. Risks of anticoagulant rodenticides to Tasmanian raptors. Tasmanian Bird Rep. 38, 17–25.

Moro, D., 2001. Evaluation and cost-benefits of controlling house mice (Mus domesticus) on islands: an example from Thevenard Island, Western Australia. Biol. Conserv. 99, 355–364.

Morris, K.D., 2002. The eradication of the black rat (*Rattus rattus*) on Barrow and adjacent islands off the north-west coast of Western Australia. In: Veitch, C.R., Clout, M.N. (Eds.), Turning the Tide: The Eradication of Invasive Species. IUCN Species Survival Commission, Gland, Switzerland, pp. 219–225.

National Registration Authority For Agricultural and Veterinary Chemicals, 2002. The NRA Review of PINDONE. Canberra, Australia.

New South Wales Department of Primary Industries, 2011. Mouse monitoring and baiting [WWW Document]. http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0008/387719/mouse-monitoring-and-baiting.pdf, Accessed date: 21 August 2017.

New South Wales Government, 2017. Department of Primary Industries. Mouse Baiting FAQs [WWW Document] http://www.dpi.nsw.gov.au/biosecurity/vertebrate-pests/pest-animals-in-nsw/mouse-and-mice-plagues/mouse-baiting-faqs#Rodenticides (accessed 8.24.17).

Nogeire, T.M., Lawler, J.J., Schumaker, N.H., Cypher, B.L., Phillips, S.E., 2015. Land use as a driver of patterns of rodenticide exposure in modeled kit fox populations. PLoS One 10, E0133351. https://doi.org/10.1371/journal.pone.0133351.

Oliver, A.J., Wheeler, S.H., Gooding, C.D., 1982. Field evaluation of 1080 and Pindone Oat Bait, and the possible decline in effectiveness of poison baiting for the control of the rabbit, *Oryctolagus cuniculus*. Aust. Wildl. Res. 9, 125–134.

Olsen, P.D., 1996. Re-establishment of an endangered subspecies: the Norfolk Island Boobook Owl Ninox novaeseelandiae undulata. Bird Conserv. Int. 6:63–80. https://doi.org/10.1017/S0959270900001313.

Olsen, J., Debus, S.J.S., Judge, D., 2013. Declining little eagles *Hieraaetus morphnoides* and increasing rabbit numbers near Canberra: is secondary poisoning by pindone the problem? Corella 37, 33–35.

Olsson, M., Wapstra, E., Swan, G., Snaith, E., Clarke, R., Madsen, T., 2005. Effects of long-term fox baiting on species composition and abundance in an Australian lizard community. Austral Ecol. 30:907–913. https://doi.org/10.1111/j.1442-9993.2005.01534.x.

Osborne, N.J., Cairns, R., Dawson, A.H., Chitty, K.M., Buckley, N.A., 2017. Epidemiology of coronial deaths from pesticide ingestion in Australia. Int. J. Hyg. Environ. Health 220:478–484. https://doi.org/10.1016/j.ijheh.2017.01.009.

Ozanne-Smith, J., Day, L., Parsons, B., Tibballs, J., Dobbin, M., 2001. Childhood poisoning: access and prevention. J. Paediatr. Child Health 37, 262–265.

Palmer, R., 2014. Eradication of the Pacific Rat (Rattus exulans) from Adele Island Nature Reserve, Western Australia: Impacts of the October 2013 aerial baiting on non-target species. Western Australia Department of Parks and Wildlife, Wanneroo, Western Australia.

Paltridge, R., 2002. The diets of cats, foxes and dingoes in relation to prey availability the Tanami Desert, Northern Territory. Wildl. Res. 29, 389–403.

Park, B., Scott, A., Wilson, A., Haynes, B., Breckenridge, A., 1984. Plasma disposition of vitamin K1 in relation to anticoagulant poisoning. Br. J. Clin. Pharmacol. 18:655–662. https://doi.org/10.1111/j.1365-2125.1984.tb02526.x.

Parsons, B.J., Day, L.M., Ozanne-Smith, J., Dobbin, M., 1996. Rodenticide poisoning among children. Aust. N. Z. J. Public Heal. 20, 488–492.

Pitt, W.C., Higashi, M., Primus, T.M., 2011. The effect of cooking on diphacinone residues related to human consumption of feral pig tissues of feral pig tissues. Food Chem. Toxicol. 49:2030–2034. https://doi.org/10.1016/j.fct.2011.05.014.

Pitt, W.C., Berentsen, A.R., Shiels, A.B., Volker, S.F., Eisemann, J.D., Wegmann, A.S., Howald, G.R., 2015. Non-target species mortality and the measurement of brodifacoum rodenticide residues after a rat (Rattus rattus) eradication on Palmyra Atoll, tropical Pacific. Biol. Conserv. 185:36–46. https://doi.org/10.1016/j.biocon.2015.01.008.

Poché, R.M., 1988. Rodent tissue residue and secondary hazard studies with bromadiolone. OEPP/EPPO Bull. 18:323–330. https://doi.org/10.1111/j.1365-2338.1988.tb00382.x.

Priddel, D., Carlile, N., Wheeler, R., 2000. Eradication of European rabbits (*Oryctolagus cuniculus*) from Cabbage Tree Island, NSW, Australia, to protect the breeding habitat of Gould's petrel (*Pterodroma leucoptera* leucoptera). Biol. Conserv. 94, 115–125.

Priddel, D., Carlile, N., Wilkinson, I., Wheeler, R., 2011. Eradication of exotic mammals from offshore islands in New South Wales, Australia. In: Veitch, C.R., Clout, M.N., Towns, D.R. (Eds.), Island Invasives: Eradication and Management. IUCN, Gland, Switzerland, pp. 337–344.

Reece, R.L., Scott, P.C., Forsyth, W.M., Gould, J.A., Barr, D.A., 1985. Toxicity episodes involving agricultural chemicals and other substances in birds in Victoria, Australia. Vet. Rec.:525–527 https://doi.org/10.1136/vr.117.20.525.

Reith, D.M., Pitt, W.R., Hockey, R., 2001. Childhood poisoning in Queensland: an analysis of presentation and admission rates. J. Paediatr. Child Health 37, 446–450.

Riley, S.P.D., Bromley, C., Poppenga, R.H., Uzal, F.A., Whited, L., Sauvajot, R.M., 2007. Anticoagulant exposure and notoedric mange in bobcats and mountain lions in urban Southern California. J. Wildl. Manag. 71:1874–1884. https://doi.org/10.2193/2005-615.

Robertson, I., Leggoe, M., Dorling, P., Shaw, S., Clark, W., 1992. A retrospective study of poisoning cases in dogs and cats: comparison between a rural and an urban practice. Aust. Vet. J. 69, 194–195.

Robinson, M.H., Wheeler, S.H., 1983. A radiotracking study of four poisoning techniques for control of the European rabbit, *Oryctolagus cuniculus* (L.). Aust. Wildl. Res. 10, 513–520.

Roll, U., Feldman, A., Novosolov, M., Allison, A., Bauer, A.M., Bernard, R., Böhm, M., Castro-Herrera, F., Chirio, L., Collen, B., Colli, G.R., Dabool, L., Das, I., Doan, T.M., Grismer, L.L., 2017. The global distribution of tetrapods reveals a need for targeted reptile conservation. Nat. Ecol. Evol. 1:1677–1682. https://doi.org/10.1038/s41559-017-0332-2.

Rueda, D., Campbell, K.J., Fisher, P., Cunninghame, F., Ponder, J.B., 2016. Biologically significant residual persistence of brodifacoum in reptiles following invasive rodent eradication, Galapagos Islands, Ecuador. Conserv. Evid. 13, 38.

Sánchez-Barbudo, I.S., Camarero, P.R., Mateo, R., 2012. Primary and secondary poisoning by anticoagulant rodenticides of non-target animals in Spain. Sci. Total Environ. 420:280–288. https://doi.org/10.1016/j.scitotenv.2012.01.028.

Saunders, G.R., 1983. Evaluation of mouse-plague control techniques in irrigated sunflower crops. Crop Prot. 2:437–445. https://doi.org/10.1016/0261-2194(83)90064-9.

Saunders, G., Kay, B., Parker, B., 1990. Evaluation of a warfarin poisoning programme for feral pigs (*Sus scrofa*). Aust. Wildl. Res. 17, 525–533.

Scelza, B.A., Bird, D.W., Bird, R.B., 2017. Bush Tucker, shop Tucker: production, consumption, and diet at an aboriginal outstation. Ecol. Food Nutr. 53:98–117. https://doi.org/10.1080/03670244.2013.772513.

Shore, R.F., Walker, L.A., Potter, E.D., Pereira, G., 2016. Second Generation Anticoagulant Rodenticide Residues in Barn Owls 2015. Lancaster, UK.

Tasmania Parks and Wildlife Sevice, 2014. 2014 Evaluation Report: Macquarie Island Pest Eradication Project. Hobart, Tasmania.

Thomas, M.O.W.G., Kutt, A.S., 1997. Owl Populations and Habitat: Factors That Could Impact Populations of Native Owls in the Sugarcane Growing Areas in Queensland, Australian Centre for Tropical Freshwater Research. James Cook University of North Queensland, Townsville https://doi.org/10.1017/CBO9781107415324.004.

Thomas, P.J., Mineau, P., Shore, R.F., Champoux, L., Martin, P.A., Wilson, L.K., Fitzgerald, G., Elliott, J.E., 2011. Second generation anticoagulant rodenticides in predatory birds: probabilistic characterisation of toxic liver concentrations and implications for predatory bird populations in Canada. Environ. Int. 37:914–920. https://doi.org/10.1016/j.envint.2011.03.010.

Tosh, D.G., Shore, R.F., Jess, S., Withers, A., Bearhop, S., Ian Montgomery, W., McDonald, R.A., 2011. User behaviour, best practice and the risks of non-target exposure associated with anticoagulant rodenticide use. J. Environ. Manag. 92:1503–1508. https://doi.org/10.1016/j.jenvman.2010.12.014.

Twigg, L.E., Singleton, G.R., Kay, B.J., 1991. Evaluation of Bromadiolone against house mouse (*Mus domesticus*) populations in irrigated soybean crops. I. Efficacy of control. Wildl. Res. 18, 265–274.

Twigg, L.E., Lowe, T.J., Martin, G.R., Gray, G.S., 1999. A Review of the Anticoagulant Pesticide Pindone.

Ward, D.J., 2008. An Ecological Assessment of Secondary Poisoning Risk in the Australian Sugarcane Industry. Queensland University of Technology.

Wedding, C.J., Weihong, J., Brunton, D.H., 2010. Implications of visitations by shore skinks *Oligosoma smithi* to bait stations containing brodifacoum in a dune system in New Zealand. Pac. Conserv. Biol. 16, 86–91.

Weir, S.M., Yu, S., Talent, L.G., Maul, J.D., Andreson, T.A., Salice, C.J., 2015. Improving reptile ecological risk assessment: oral and dermal toxicity of pesticides to a common lizard species (*Sceloporus occidentalis*). Environ. Toxicol. Chem. 34:1778–1786. https://doi.org/10.1002/etc.2975.

Woinarski, J.C.Z., Burbidge, A.A., Harrison, P.L., 2015. Ongoing unraveling of a continental fauna: decline and extinction of Australian mammals since European settlement. Proc. Natl. Acad. Sci. 112:4531–4540. https://doi.org/10.1073/pnas.1417301112.

Young, J., De Lai, L., 1997. Population declines of predatory birds coincident with the introduction of Klerat rodenticide in North Queensland. Aust. Bird Watch. 17, 160–167.