Review of rodent control for the Australian chicken meat and egg industries

by Alex Howard, David Hamilton, and Jessica Jolley
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South Australian Research and Development Institute

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Foreword

In Australia, rodent control has historically relied on the heavy use of pesticides. In recent years, heavy pesticide use has come under increasing scrutiny, with growing awareness of animal ethics, efficacy, environmental safety and best practice chemical use. This report, co-funded by Australia Eggs Limited, details the methodology and findings of a review of rodent control for the Australian chicken meat and egg industries undertaken by the South Australian Research and Development Institute from July 2018 to December 2019. This review consists of a national survey of rodent observations, rodent control and rodenticide use in the Australian chicken meat and egg industries as well as a comprehensive literature review of available and emerging rodent control products, strategies and technologies.

The aim of this document is to raise awareness of the advantages, disadvantages, risks and regulatory requirements associated with specific active compounds, and provide producers with an objective comparison of all rodenticides currently registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Information is also included relating to target species behaviour and ecology, integrated rodent management strategies as well as novel and emerging rodent control products. The listing of any rodenticide or trade name of any rodenticide in this report does not constitute or imply endorsement of that pesticide by the authors. The approved use of rodenticides is dependent on state and federal legislation, which may vary across location and time. Users should refer to the APVMA website (https://apvma.gov.au/) for the most up-to-date information.

Australian chicken meat and egg producers and processors, as well as industry associations, will all benefit from this work. The integration of the information contained in this report will enable producers to employ improved rodent control strategies, which will have flow-on effects for the entire poultry industry.

The survey of current industry rodent control practices found that rodent control in Australian poultry operations is primarily based on the use of poison baits, specifically anticoagulant rodenticides. If used appropriately, and in conjunction with a range of physical management strategies, these compounds can be an effective tool for the management of rodents on-farm. If used inappropriately, the inherent risks associated with these compounds could negatively impact the profitability, productivity and integrity of the Australian chicken meat and egg industries.

This project will provide an opportunity for the Australian chicken meat and egg industry bodies to update national rodent control manuals and inform producers of relevant and effective options for rodent control and rodenticide use. This research will assist in maintaining the productivity, profitability and long-term financial viability of the chicken meat and egg industries through the improved on-farm management of rodents.

This report for the AgriFutures Chicken Meat Program adds to AgriFutures Australia's diverse range of over 2000 research publications. It forms part of our Growing Profitability arena, which aims to enhance the profitability and sustainability of our levied rural industries.

Most of AgriFutures Australia's publications are available for viewing, free downloading or purchasing online at: www.agrifutures.com.au.

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Abbreviations and glossary

APVMA: Australian Pesticides and Veterinary Medicines Authority.

AR: Anticoagulant rodenticides – compound that blocks the vitamin K cycle, resulting in the inability to produce essential blood-clotting factors.

Half-life: The period of time required for the concentration or amount of drug to be reduced by 50%.

LD_{50} (lethal dose 50% or median lethal dose): The dose of a compound required to kill half of the members of a tested population over a specified time. Oral LD_{50} is measured in mg of toxin/kg of bodyweight of the animal.

Neophilic: The behavioural tendency to explore or investigate new or novel things.

SGAR: Second-generation anticoagulant rodenticide – class of ARs with greater potency and a longer half-life than first-generation ARs, enabling these compounds to be effective against resistant rodent strains.

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Executive summary

What the report is about

This report details the methodology and findings of a review of rodent control for the Australian chicken meat and egg industries undertaken by the South Australian Research and Development Institute from July 2018 to December 2019. The review consists of a national survey of rodent observations, rodent control, and rodenticide use in the Australian chicken meat and egg industries as well as a comprehensive literature review of available and emerging rodent control products, strategies and technologies.

Who is the report targeted at?

The target audience for this report are Australian chicken meat and egg layer producers and processors, as well as industry associations.

Where are the relevant industries located in Australia?

The Australian egg industry has the following geographic distribution according to state flock percentage: NSW/ACT (33.0%), VIC (25.7%), QLD (25.2%), WA (8.3%), SA/NT (6.7%) and TAS (1.2%). As of June 2019, the national flock size is 20.9 million layers. In the 2018-19 financial year, 518 million dozen eggs were produced in Australia (Australian Eggs Limited Annual Report, 2019).

The Australian chicken meat industry has the following geographic distribution according to the percentage of chickens slaughtered: NSW (31.9%), QLD (20.8%), VIC (19.6%) and SA+WA+TAS (27.7%). In the 2017-18 financial year, a total of 664 million chickens were slaughtered, equating to 1.2 million tonnes of chicken meat (Australian Chicken Meat Federation – Facts and Figures, 2017/18).

Background

Rodent infestations are a persistent issue affecting Australia's chicken meat and egg laying industries. Rodents pose a major risk to food safety and food hygiene through contamination of feed. They are able to transmit disease-causing organisms through their feet, fur, saliva, droppings, urine and blood. Rodents can also cause significant damage to farm facilities because they chew through walls, insulation and wiring to gain access to food and to scavenge building materials for their nests and burrows. This can compromise the structural integrity of shed walls, floors and ceilings, undermine disease barriers, and create energy inefficiencies that increase operating costs. Rodent control is therefore a key part of a farm's biosecurity strategy and must be appropriately considered and implemented to mitigate the risks outlined above. This project was developed to address knowledge gaps and to raise awareness of the current state of rodent control across the Australian chicken meat and egg industries.

Aims/objectives

The objectives of this project are to:

1. Survey the current use of rodenticides in Australian chicken meat production systems
2. Survey the current use of rodenticides in Australian layer production systems
3. Prepare a literature review of available and emerging rodent control products that are suitable for use in the Australian chicken meat and egg industries.

Methods used

The methodology for the project stages were as follows:

1. Survey of industry rodent control practices

- Initiated preliminary conversations with industry stakeholders (chicken meat and eggs).
- Developed a four-page survey questionnaire through consultation with the steering committee, with questions relating to production systems, rodent observations, rodent control protocols, rodent control products and services, rodent control practices, and producer thoughts (Appendix 1).
- Conducted surveys over the phone, email and face-to-face.
- Made efforts to capture responses from a range of production systems (for layers: barn, free range, caged, organic; and for chicken meat: conventional, free range, organic).
- Sought responses from producers located in all poultry-producing states and territories in Australia.

2. Literature review of available and emerging rodent control products
    - Systematic review of rodenticide product information and scientific literature using internet searches and academic article databases.
    - 485 scientific papers screened to identify relevant publications relating to rodenticides, rodent behaviour and rodent ecology.

Results/key findings

The survey of current industry rodent control practices found that control in Australian poultry operations primarily consists of the use of poison baits, specifically, anticoagulant rodenticides. If used appropriately, and with a range of physical management strategies, these compounds can be an effective tool for managing rodents on-farm. But if used inappropriately, the inherent risks associated with these compounds could affect the profitability, productivity and integrity of the Australian chicken meat and egg laying industries.

The literature review delivers a comprehensive review of scientific literature on available and emerging rodent control products suitable for use in chicken meat and egg (layer) production systems. The document raises awareness of the advantages, disadvantages, risks and regulatory requirements associated with specific active compounds. It gives producers an objective comparison of all rodenticides currently registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Information about target species behaviour and ecology, integrated rodent management strategies, and novel and emerging rodent control products is also included.

Outputs from this project provide an opportunity for the Australian chicken meat and egg industry bodies to update national manuals and to inform producers of relevant and effective options for rodent control and rodenticide use. This research will help maintain the productivity, profitability and long-term financial viability of the chicken meat and egg industries through better management of rodents on-farm.

Implications for relevant stakeholders

Rodents are a widespread and persistent issue for the Australian chicken meat and egg industries. This project directly implicates rodents as a cause of significant levels of farm structural and property damage and a threat to food safety and food hygiene. The economic burden associated with rodent infestations is difficult to quantify given their insidious nature and hidden impact. The total cost of rodent infestations, which includes structural repairs, feed loss, production loss, disease incidents, energy inefficiencies, and the implementation of year-round rodent control programs, is likely to be significant.

Potential benefits stemming from this research include better management of rodents on-farm, better poultry bird health and the prevention of disease transmission from rodents. Reductions in rodent populations on-farm will also lead to less structural damage, feed loss and contamination commonly caused by rodents. Appropriate and efficient use of rodenticides in conjunction with physical

management strategies, such as rodent habitat disruption and physical exclusion, will reduce the risk of non-target poisoning of livestock, native wildlife species and domestic animals.

Recommendations

The recommendations from this research are targeted at the relevant industry research and development corporations, namely AgriFutures Chicken Meat Program and Australian Eggs Limited. Current industry information and documentation relating to the management of rodents in poultry operations needs to be updated to provide producers with accurate and up-to-date information to improve on-farm management of rodents. The literature review from this project should be made available to Australian poultry producers, and practical elements should be published in the next updated versions of the national biosecurity manuals for chicken meat and egg layer production.

Two recommendations are made from the results of the industry survey:

- It is strongly recommended that baits be securely fixed inside enclosed bait stations, using wire, a tie-down or a skewer. Less secure bait-housing methods (e.g. homemade PVC bait housing, bait placed in brown paper bags, or improvised containers) are not recommended because rodents are known to hoard food sources (including bait). Bait that is not securely housed could become scattered around production areas of farms, resulting in a higher risk of contamination or secondary poisoning.
- Producers are encouraged to refer to the instructions of use for particular rodenticide products, and to closely monitor and record the level of bait intake and rodent activity at each of their bait stations.

Introduction

Rodent infestations are a feature of rural Australia, affecting grain growers, intensive livestock industries and rural communities. For Australian poultry farmers (breeders, meat chicken and layers) in particular, it is a constant battle to keep rodents at bay. Commercial poultry sheds and farm structures provide an attractive artificial habitat for rats (*Rattus norvegicus* and *Rattus rattus*) and mice (*Mus musculus*), with abundant food and water as well as protection from natural predators.

Risks from rodents include rodent-borne diseases, animal welfare (harassment and biting by rodents), feed losses, contamination, and structural damage. Rodents can spread or accelerate the spread of disease from contaminated areas to uncontaminated areas via their droppings, feet, fur, urine, saliva or blood. Through their gnawing and burrowing, rodents are also responsible for a vast amount of damage to wiring and shed infrastructure. When rodents live around farm buildings, they are a food source that can attract predators, such as foxes, stray cats or snakes, which, in turn, can contribute to disease problems or loss of stock. Unless rodents are well controlled, an effective disease barrier system cannot be achieved or maintained.

Rodent control is a key requirement of a farm's biosecurity strategy and must be properly considered and implemented to mitigate the risks outlined above. Currently, available industry resources for producers are the *National Farm Biosecurity Manual for Chicken Growers* (latest version December 2019) and the *National Farm Biosecurity Technical Manual for Egg Production* (latest version April 2015, currently being updated). These manuals instruct producers to limit rodent access, develop and implement an appropriate rodent control strategy, and implement baiting programs where a risk assessment deems it necessary. Despite recent research advancements, these manuals provide limited information to producers on current products, their effectiveness, availability, implementation and suitability for different situations (for example, normal operations vs plague outbreaks).

This project aims to raise awareness of the issues associated with rodents and provide an overview of the current status of rodent control in the Australian chicken meat and egg laying industries. It has also culminated in the development of a comprehensive literature review of available and emerging rodent control products, strategies and technologies. The outputs from this project provide an opportunity for the Australian chicken meat and egg industry bodies to update national manuals and to inform producers of relevant and effective options for rodent control and rodenticide use. This has the potential to directly improve on-farm rodent management and will help maintain the productivity, profitability and long-term financial viability of the industries.

Objectives

The objectives of this project are to:

1. Survey the current use of rodenticides in Australian chicken meat production systems
2. Survey the current use of rodenticides in Australian layer production systems
3. Prepare a literature review of available and emerging rodent control products that are suitable for use in the Australian chicken meat and egg industries.

Methodology

Rodent control survey

In June 2018, researchers initiated conversations with the project steering committee, which included representatives from AgriFutures Chicken Meat Program and Australian Eggs Limited as well as a commercial layer farm manager and a meat chicken technical and welfare manager. Steering committee members were introduced to the research team and feedback was sought on the approach for the industry survey and literature review.

A four-page survey questionnaire containing 29 questions was developed and divided into sections relating to production systems, rodent observations, rodent control protocols, rodent control products and services, rodent control practices, and producer thoughts (Appendix 1). Industry representatives from the steering committee provided the first responses to the survey and invited researchers to visit their operations to observe on-farm rodent control practices and provide context to the questionnaire responses.

In December 2018, representatives from Australian Eggs and from AgriFutures Chicken Meat Program helped the project by distributing the survey to some farm managers and producers or by introducing contacts in their respective professional networks. Through contacts in the state departments of agriculture, a database containing the contact details of chicken meat and layer producers was developed. Other producers were contacted and asked to participate in the survey. Survey responses were reviewed as they were received and, where necessary, producers were contacted to clarify responses. Efforts were made to survey producers with a wide range of production systems (for layers: barn, free range, caged, organic; and for chicken meat: conventional, free range, organic). Because this is a national survey, responses were sought from producers in all poultry-producing states and territories. Several external rodent control contractors were also contacted and asked for feedback and information about rodent control practices in poultry production settings.

Literature review

In December 2018, a systematic literature search was performed and relevant publications were retrieved from the Web of Science database through access to the University of Adelaide Library. Web of Science is a platform of multidisciplinary and scientific abstracts databases, including Web of Science Core Collection, Biosis Citation Index, CAB Abstracts and Global Health, Current Contents Connect, FSTA-the food science resource, Medline, Russian Citation Index, SciELO Citation Index and Zoological Record. No language restrictions were applied.

Initially, a broad scan of literature was conducted using the search terms; “Rodent Control”, “Rodenticide” and “Vertebrate Pests”. These search terms produced 485 results. Titles and abstracts of these papers were reviewed by a single person to identify relevant publications. Additional searches of the Web of Science database and Google Scholar academic search engine retrieved supplementary literature relating to specific rodenticides, rodent behaviour and rodent ecology. In total, 146 papers were included in the final literature review.

The Australian Pesticides and Veterinary Medicines Authority (APVMA) Public Chemical Registration Information System database was also searched to generate a list of all chemical rodenticide products and their manufacturers that are registered for sale and use in Australia. Information relating to their use, permit requirements, available formulations, mode of action, level of toxicity and secondary poisoning risk is summarised in the Rodenticide product manual section of the literature review.

Results

Rodent control survey

A four-page survey questionnaire containing 29 questions was developed and distributed to Australian chicken meat and egg laying producers from 2018-19 (Appendix 1). The objectives of the survey were to:

- Survey use of rodenticides in both industries
- Identify broad industry rodent control practices
- Identify the level of burden that rodents pose to chicken meat and egg layer production.

Questions were separated into six sections: 1) production system features; 2) rodent observations; 3) rodent control protocols; 4) rodent control products and services; 5) rodent control practices; and 6) producer thoughts and feedback.

Producer survey results

Survey responses were received from 36 Australian layer producers from all egg-producing states and territories. In total, survey responses were received from producers with a total maximum capacity of 13.6 million laying birds. The national flock size is estimated to be 20.9 million laying birds (Australian Eggs Annual Report, June 2019). Therefore, this survey has covered roughly 62% of Australian production.

Researchers made significant efforts to have survey responses from individual chicken meat farm managers, as was the practice with the chicken layer survey. However, due to the vertical integrated nature of the industry, state and/or national representatives of major chicken meat-producing companies were often delegated the responsibility of providing responses on behalf of farm managers. These responses gave an indication of company-wide rodent control protocols and practices but lacked the level of detailed information about on-farm day-to-day observations of rodent activity.

In total, responses were received from producers responsible for a total annual production of roughly 285 million birds, which represents 43% of the total Australian market (Australian Chicken Meat Federation Industry Facts & Figures 2017/18). Responses received from individual farm managers represented roughly 15% of Australian chicken meat production.

The level of burden posed by rodents and the range of rodent control practices used were found to be comparable for both chicken meat and egg layer producers. Therefore, the survey responses presented and discussed below have been combined for both the chicken meat and egg layer industries. In total, 41 survey responses were received. However, responses from producers with multiple production systems were separated during the analysis of results in order to understand the rodent observations associated with different production systems, increasing the number of unique survey responses to 55.

Survey responses from both industries were received with the following geographic distribution: QLD (29.1%), VIC (25.5%), NSW (16.4%), SA (10.9), WA (7.3%), TAS (5.5%) and the ACT (3.6%) (Table 1). A total of 52/55 (94.5%) of producers surveyed commonly observed on-farm rodent activity, while 100% had observed rodents on-farm in either the past or present. This result indicates that rodents are a persistent and widespread issue for the Australian chicken meat and egg laying industries.

An insufficient number of responses were received from states/territories with a smaller proportion of production to determine whether the level of rodent observation or offending rodent species were unique to a particular state or territory. However, respondents anecdotally reported that geographical location, in particular, proximity to shelter and other food sources, were factors that directly influence the level of rodent activity.

A summary of the survey responses for each of the unique production systems, which include Free Range (Meat chicken and Layer combined), Barn/Conventional (Meat chicken and Layer combined), Caged (Layer only) and Organic (Layer only), is presented in Tables 2 to 6. Producers with all production systems frequently observed rodents; no apparent relationship was observed between the type of production system and the level of rodent observation. However, layer producers with a mixture of production systems commented that rodents were easier to manage in caged production systems, given that birds were housed off the floor in secure cages, allowing for baits to be placed within the internal areas of sheds.

Tables 2 to 6 are structured to show the responses received from producers with different scales of operation (total number of producing birds). Results demonstrate that while rodent observations were fairly common among all production sizes, smaller scale producers (<1000–20,000 birds) typically observed lower levels of rodent activity than large producers. This result was supported by comments from smaller producers that small operations lack the amount of food and harbourage to attract the numbers of vermin that large-scale producers do.

The most common offending rodent species were the house mouse (*Mus musculus*), observed on 73% of operations, and rats (*Rattus* sp.) observed on 71% of farms. Roughly half of the survey respondents (52%) observed rats and mice on their farms. Several producers commented that the presence of mice was inevitable but that visible observations of rats indicated a severe rodent problem. Eight producers identified rats on their farms as brown/Norway rats (*Rattus norvegicus*), three identified black rats (*Rattus rattus*) and the majority (28 producers) were unable to identify the rat species. The literature review accompanying this final report (Appendix 2) contains useful information for producers about identifying rodent species from physical and behavioural features. Correctly identifying the offending on-farm rodent species will allow for targeted rodent control strategies, increasing the likelihood that these efforts will succeed.

Table 1: Response to rodent control survey, incidence of rodent observation and rodent species observed, according to the state/territory location of chicken layer operations.

State/territory	*Number of responses*	*Proportion of respondents*	*Proportion that observe rodents*	*Rodent species observed*
QLD	16	29.1%	93.8%	Brown rats and mice
VIC	14	25.5%	100%	Brown rats (predominantly), some black rats and mice
NSW	9	16.4%	88.9%	Brown rats, black rats and mice
SA	6	10.9%	100%	Mice (predominantly), some rats
WA	4	7.3%	100%	Mice (predominantly), some rats
TAS	3	5.5%	100%	Mice (predominantly), some rats
ACT	2	3.6%	50%	Rats and mice (rare)
Anonymous	1	1.8%	100%	Rats and mice
Total	***55***		***52/55 (94.5%)***	

Table 2: Summary of Free Range (Chicken meat and Layer combined) survey responses according to size of production (total number of producing birds).

	Free Range (Layers and Chicken meat)				
Flock size (number of birds)	**<1000**	**1000-20,000**	**20,000-200,000**	**>200,000**	***Total***
Number of responses	2	9	5	11	***27***
Questions					
Rodent activity					
Rodent activity observed	1/2 (50%)	7/9 (78%)	5/5 (100%)	11/11 (100%)	***24/27 (89%)***
Rodent activity not observed	1/2 (50%)	2/9 (22%)	-	-	***3/27 (11%)***
Rodent species, if observed					
Rats and mice	1/1 (100%)	6/7 (86%)	2/5 (40%)	6/11 (55%)	***15/24 (63%)***
Rats only	-	-	1/5 (20%)	4/11 (36%)	***5/24 (21%)***
Mice only	-	1/7 (14%)	2/5 (40%)	1/11 (9%)	***4/19 (17%)***
Rodent-related incidents					
Rodent-related incidents observed	-	4/9 (44%)	4/5 (80%)	5/11 (45%)	***13/27 (48%)***
Rodent-related incidents not observed	2/2 (100%)	5/9 (56%)	1/5 (20%)	6/11 (55%)	***14/27 (52%)***
Formal rodent control protocol					
Written protocol for rodent control	1/2 (50%)	5/9 (56%)	4/5 (80%)	11/11 (100%)	***21/27 (78%)***
No written rodent control protocol	1/2 (50%)	4/9 (44%)	1/5 (20%)	-	***6/27 (22%)***
Rodent control contractor usage					
External contractor used	-	3/9 (33%)	2/5 (40%)	2/11 (18%)	***7/27 (26%)***
No external contractors used	2/2 (100%)	6/9 (66%)	3/5 (60%)	9/11 (82%)	***20/27 (74%)***
Baiting					
Rodenticides in use	1/2 (50%)	7/9 (78%)	5/5 (100%)	11/11 (100%)	***24/27 (89%)***
No rodenticides used	1/2 (50%)	2/9 (22%)	-	-	***3/27 (11%)***

Table 3: Summary of Barn and Conventional (Chicken meat and Layer combined) survey responses according to size of production (total number of producing birds).

	Barn & Conventional (Layers and Chicken meat)				
Flock size (number of birds)	**<1000**	**1000-20,000**	**20,000-200,000**	**>200,000**	***Total***
Number of responses	-	-	5	8	***13***
Questions					
Rodent activity					
Rodent activity observed	-	-	5/5 (100%)	8/8 (100%)	***13/13 (100%)***
Rodent activity not observed	-	-	-	-	***-***
Rodent species, if observed					
Rats and mice	-	-	1/5 (20%)	5/8 (63%)	***6/13 (46%)***
Rats only	-	-	1/5 (20%)	3/8 (37%)	***4/13 (31%)***
Mice only	-	-	3/5 (60%)	-	***3/13 (23%)***
Rodent-related incidents					
Rodent-related incidents observed	-	-	4/5 (80%)	3/8 (38%)	***7/13 (54%)***
Rodent-related incidents not observed	-	-	1/5 (20%)	5/8 (62%)	***6/13 (46%)***
Formal rodent control protocol					
Written protocol for rodent control	-	-	4/5 (80%)	8/8 (100%)	***12/13 (92%)***
No written rodent control protocol	-	-	1/5 (20%)	-	***1/13 (8%)***
Rodent control contractor usage					
External contractor used	-	-	2/5 (40%)	2/8 (25%)	***4/13 (31%)***
No external contractors used	-	-	3/5 (60%)	6/8 (75%)	***9/13 (69%)***
Baiting					
Rodenticides in use	-	-	5/5 (100%)	8/8 (100%)	***13/13 (100%)***
No rodenticides used	-	-	-	-	***-***

Table 4: Summary of Caged (Layer only) survey responses according to size of production (total number of producing birds).

	Caged (Layer only)				
Flock size (number of birds)	**<1000**	**1000-20,000**	**20,000-200,000**	**>200,000**	***Total***
Number of responses	-	2	4	7	***13***
Questions					
Rodent activity					
Rodent activity observed	-	2/2 (100%)	4/4 (100%)	7/7 (100%)	***13/13 (100%)***
Rodent activity not observed	-	-	-	-	**-**
Rodent species, if observed					
Rats and mice	-	1/2 (50%)	2/4 (50%)	2/7 (29%)	***5/13 (38%)***
Rats only	-	-	-	3/7 (43%)	***3/13 (23%)***
Mice only	-	1/2 (50%)	2/4 (50%)	2/7 (29%)	***5/13 (38%)***
Rodent-related incidents					
Rodent-related incidents observed	-	2/2 (100%)	2/2 (50%)	6/7 (86%)	***10/13 (77%)***
Rodent-related incidents not observed	-	-	2/2 (50%)	1/7 (14%)	***3/13 (23%)***
Formal rodent control protocol					
Written protocol for rodent control	-	1/2 (50%)	2/4 (50%)	7/7 (100%)	***10/13 (77%)***
No written rodent control protocol	-	1/2 (50%)	2/4 (50%)	-	***3/13 (23%)***
Rodent control contractor usage					
External contractor used	-	2/2 (100%)	2/4 (50%)	2/7 (29%)	***6/13 (46%)***
No external contractors used	-	-	2/4 (50%)	5/7 (71%)	***7/13 (54%)***
Baiting					
Rodenticides in use	-	2/2 (100%)	4/4 (100%)	7/7 (100%)	***13/13 (100%)***
No rodenticides used	-	-	-	-	**-**

Table 5: Summary of Organic (Layer only) survey responses according to size of production (total number of producing birds).

	Organic (Layer only)				
Flock size (number of birds)	**<1000**	**1000-20,000**	**20,000-200,000**	**>200,000**	***Total***
Number of responses	-	-	2	-	***2***
Questions					
Rodent activity					
Rodent activity observed	-	-	2/2 (100%)	-	***2/2 (100%)***
Rodent activity not observed	-	-	-	-	**-**
Rodent species, if observed					
Rats and mice	-	-	1/2 (50%)		***1/2 (50%)***
Rats only	-	-	-	-	**-**
Mice only	-	-	1/2 (50%)	-	***1/2 (50%)***
Rodent-related incidents					
Rodent-related incidents observed	-	-	1/2 (50%)	-	***1/2 (50%)***
Rodent-related incidents not observed	-	-	1/2 (50%)	-	***1/2 (50%)***
Formal rodent control protocol					
Written protocol for rodent control	-	-	2/2 (100%)	-	***2/2 (100%)***
No written rodent control protocol	-	-	-	-	**-**
Rodent control contractor usage					
External contractor used	-	-	-	-	**-**
No external contractors used	-	-	2/2 (100%)	-	***2/2 (100%)***
Baiting					
Rodenticides in use	-	-	2/2 (100%)	-	***2/2 (100%)***
No rodenticides used	-	-	-	-	**-**

Table 6: Summary of Chicken meat and Layer survey responses for each production system. 55 survey responses were received.

	Free range (Layers and Chicken meat)	**Barn & Conventional (Layers and Chicken meat)**	**Caged (Layers only)**	**Organic (Layers)**	***Total across all production systems***
Number of responses	27	13	13	2	***55***
Questions					
Rodent activity					
Rodent activity observed	24/27 (89%)	13/13 (100%)	13/13 (100%)	2/2 (100%)	***52/55 (95%)***
Rodent activity not observed	3/27 (11%)	-	-	-	***3/55 (5%)***
Rodent species, if observed					
Rats and mice	15/24 (63%)	6/13 (46%)	5/13 (38%)	1/2 (50%)	***27/52 (52%)***
Rats only	5/24 (21%)	4/13 (31%)	3/13 (23%)	-	***12/52 (23%)***
Mice only	4/24 (17%)	3/13 (23%)	5/13 (38%)	1/2 (50%)	***13/52 (25%)***
Rodent-related incidents					
Rodent-related incidents observed	13/27 (48%)	7/13 (54%)	10/13 (77%)	1/2 (50%)	***31/55 (56%)***
Rodent-related incidents not observed	14/27 (52%)	6/13 (46%)	3/13 (23%)	1/2 (50%)	***24/55 (44%)***
Formal rodent control protocol					
Written protocol for rodent control	21/27 (78%)	12/13 (92%)	10/13 (77%)	2/2 (100%)	***45/55 (82%)***
No written rodent control protocol	6/27 (22%)	1/13 (8%)	3/13 (23%)	-	***10/55 (18%)***
Rodent control contractor usage					
External contractor used	7/27 (26%)	4/13 (31%)	6/13 (46%)	-	***17/55 (31%)***
No external contractors used	20/27 (74%)	9/13 (69%)	7/13 (54%)	2/2 (100%)	***38/55 (69%)***
Baiting					
Rodenticides in use	24/27 (89%)	13/13 (100%)	13/13 (100%)	2/2 (100%)	***52/55 (95%)***
No rodenticides used	3/27 (11%)	-	-	-	***3/55 (5%)***

Producers were asked to list the types of damage inflicted on their operations due to rodents (Table 7). Rodent-related damage was reported by 56% of survey respondents, with property/structural damage the most common observation. Examples of this type include damage to wall panels, roof insulation, shed blinds and egg packaging due to the gnawing and burrowing of rodents. Damage to electrical wiring, which represents a possible fire hazard, was observed by 22% of producers. Potential disease and contamination (*Salmonella* Enteritidis) were also reported by a small proportion of producers. Respondents acknowledged that it is difficult to single out rodents as the definitive cause of such incidents.

Producers were also asked to list the range of their specific on-farm rodent control methods (Table 8). Use of rodenticides was the most common rodent control method (95% of survey respondents), with anticoagulants the most common bait ingredient. Less common strategies included attempts to rodent-proof farm structures using seals and grates (38%), physical traps/glue boards (24%), and a 'bare earth policy' that involves keeping grass short around sheds, removing rubbish and potential harbourage, and tidying up feed spills (16%). Table 9 shows the range and frequency of rodenticide-active ingredients used by poultry producers. Brodifacoum, a second-generation anticoagulant rodenticide (SGAR), was the most common bait ingredient, with 60% of rodenticide users reporting use of products containing this active compound. Bromadiolone, another SGAR, and Coumatetralyl, a first-generation anticoagulant, were used by 24% and 27% of bait users, respectively. Few producers reported using baits containing the acute poisons cholecalciferol or zinc phosphide. One producer reported use of a non-toxic bait containing corn gluten meal bait (RatX®) at his two farm sites, although this was used in addition to traditional anticoagulant compounds.

Many survey respondents reported the frequent rotation of various anticoagulants with baits containing different active ingredients. Producers commented that it was an attempt to maintain the palatability of baits and prevent rodents from becoming bored with a single bait formulation. There is a lack of scientific evidence demonstrating this as an effective rodent control strategy. Furthermore, the neophobic behaviour displayed by rodents, particularly rats, likely means that frequent rotation of baits may reduce bait palatability and intake. The literature review accompanying this report (Appendix 2) contains key information that could help producers identify specific active compounds that are more likely to effectively control rodents.

Producers responded to questions about bait formulation, bait housing and bait station checking frequency; see results in Tables 10 and 11. Extruded wax blocks were the most common bait formulation. In terms of bait housing, 100% of rodenticide users reportedly used secure commercial bait stations. However, less secure bait housing methods, such as homemade PVC bait housing, bait placed in brown paper bags or improvised containers, were also used.

Responses about bait application rate and bait station checking frequency were highly variable. Many producers commented that the amount of bait and the frequency of checks changed in response to the level of rodent activity. The literature review contains some other information on baiting techniques that are relevant to specific active compounds.

Several external rodent control contractors were asked to provide feedback and information about rodent control practices in poultry production settings. They noted that poultry operations attract vermin because of the availability of feed and the provision of shelter. Several rodent control contractors commented that the requirements for retail certification dictate what can and cannot be done to combat rodents, removing some of the potential options to control them. All rodent control operators stressed the importance of an integrated rodent management strategy, which consists of a combination of physical management strategies, hygiene practices, record keeping and baiting, rather than just placing more poison bait stations.

Table 7: Layer producer observations of types of damage caused by rodents on-farm. Fifty-five survey responses were received. Where applicable, respondents listed more than one type of damage, and so the proportion of responses does not sum to 100%.

Type of damage	*Number of responses*	*Incidence*
No damage	24	44%
Property/structural damage	19	35%
Electrical wiring	12	22%
Feed loss	12	22%
Disease incident	6	11%
Contamination	2	4%

Table 8: Rodent control methods used by layer producers. Fifty-five survey responses were received. Where applicable, respondents reported use of multiple control methods and so the proportion of responses does not sum to 100%.

Rodent control method	*Number of responses*	*Proportion of use*
Anticoagulant bait	45	82%
Rodent-proof seals/walls/floors	21	38%
Traps/glue boards	13	24%
Bare earth policy	9	16%
Unknown poison bait	7	13%
Non-anticoagulant toxic bait	2	4%
Non-toxic bait	1	2%
No control method	1	2%

Table 9: Active bait ingredients used by layer producers. Of 55 survey responses received, 52 reported use of poison baits. Where applicable, respondents reported use of multiple bait active ingredients and so the proportion of responses does not sum to 100%.

Active bait ingredient	Producers using bait	Usage proportion
Acute poisons		
Cholecalciferol	2	4%
Zinc phosphide	1	2%
First-generation anticoagulants		
Coumatetralyl	15	27%
Diphacinone	3	6%
Warfarin	1	2%
Second-generation anticoagulants		
Brodifacoum	33	60%
Bromadiolone	13	24%
Difenacoum	7	13%
Difethialone	0	0%
Flocoumafen	4	7%
Other bait ingredients		
Unknown poison bait active	7	13%
Non-toxic active	2	4%

Table 10: Bait formulations used by layer producers. Of 55 survey responses received, 52 reported use of poison baits. Where applicable, respondents reported use of multiple poison bait formulations and so the proportion of responses does not sum to 100%.

Poison bait formulation	Number of responses	Proportion of responses
Wax block	45	87%
Liquid/gel	11	21%
Grain/pellet/sachet	11	21%
Tracking powder	8	15%

Table 11: Bait housing methods used by layer producers. Of 55 survey responses received, 52 reported use of poison baits. Where applicable, respondents reported use of multiple bait housing methods and so the proportion of responses does not sum to 100%.

Bait housing method	Number of responses	Proportion of use
Commercial enclosed bait station	52	100%
Handmade plastic/PVC container	6	12%
Loosely contained bait	5	10%
Drum/container	2	4%
Bait placed in brown paper bag	2	4%
Bait nailed to wall surface/rafter	1	2%

Producers were asked to rate their on-farm rodent control on a scale of 1 (useless) to 10 (very effective); results are given in Table 12. Larger scale producers generally rated their rodent control programs more highly than smaller producers. This contradicts the broad findings of the survey that showed that larger producers typically observed more frequent rodent activity. Many producers commented that they felt that environmental factors (such as rainfall and feed availability in surrounding areas) contributed to the level of rodent incursion rather than the efficacy or lack thereof of specific control measures. Producers with less successful rodent control programs attributed the issue to environmental or seasonal factors, while producers who reduced rodent numbers generally attributed their outcomes to effective baiting programs and a focus on facility maintenance, upkeep and cleaning.

Producers were queried about their views on potential issues with rodenticide use, including the detection of residues in food, the development of rodenticide resistance in rodents and the secondary poisoning of livestock, wildlife or domestic animals. Caged layer producers felt that they had the lowest risk of residue contamination or secondary poisoning because birds were physically separated from

baits and baited rodents. Free range and barn/conventional producers acknowledged that there was a level of risk, although commenting that this could be mitigated by securely housing bait and placing bait stations in areas that birds cannot access.

Table 12: Producer responses when asked "On a scale of 1 (useless) to 10 (very effective), how would you rate your rodent control program?"

Number of birds	Number of responses	Median self-rated rodent control score
>200,000	26	8/10
20,000-200,000	16	8/10
1000-20,000	11	7.75/10
<1000	2	5/10

Literature review

Below is a summary of key rodent control information taken from the review of rodent control for the Australian chicken meat and egg industries. The full version of the literature review can be found in Appendix 2.

Rodent species identification

The three main rodent pest species relevant to poultry operations in Australia are the black rat (*Rattus rattus*), Norway/brown rat (*Rattus norvegicus*) and house mouse (*Mus musculus*). Each of these rodent species has a unique set of physical features and behavioural adaptations that need to be considered when designing a rodent control program. Correctly identifying the offending rodent species on-farm will allow for targeted rodent control strategies, increasing the likelihood that rodent control efforts will succeed. Table 13 summarises the physical features and behavioural characteristics of each rodent species, which will help with identification.

Table 13: Comparison of physical features and behavioural characteristics of *Rattus rattus*, *Rattus norvegicus* and *Mus musculus*, the three main rodent pest species observed in poultry operations in Australia.

Scientific name	*Rattus rattus*	*Rattus norvegicus*	*Mus musculus*
Common names	Black rat, roof rat, ship rat, fruit rat	Norway rat, brown rat, sewer rat	House mouse, field mouse
Image			
Adult size	200-340 grams	200-480 grams	15-25 grams
Length (head+body)	150-220 mm	180-255 mm	60-90 mm
Length (tail)	180-250 mm	150-215 mm	80-100 mm
Fur & colour	Smooth and soft; black/grey/brown	Rough and shaggy; grey/brown	Sleek; brown/grey
Descriptive features	Thin, large and hairless ears; large eyes; pointed snout	Thick, opaque and fine haired ears; small eyes; blunt snout	Large ears relative to body; small eyes; pointed snout
Droppings	Scattered; pointed ends 	Grouped; rounded ends 	Scattered; pointed ends 
Habitat and behaviour	Nests in walls, roof cavities, vines and trees; agile climber; somewhat	Nests in burrows; can climb but not agile; neophobic (avoids novel objects and new foods); hoards food for	Nests in burrows or crevices; neophilic (inquisitive of novel objects and will try

	neophobic (avoids novel objects and new foods)	future consumption (including bait)	new food); good climber
Preferred diet	Omnivore: prefers fruits, nuts, grains and vegetables; will eat human waste, insects, small mammals, bird eggs and nestlings; consumes 25-30 grams per day; requires a source of fresh water	Omnivore: prefers fruits, nuts, grains and vegetables; will eat human waste, insects, small mammals, bird eggs and nestlings; more likely to eat meat than *Rattus rattus*; consumes 30 grams per day; requires a source of fresh water	Omnivore: will eat fruits, nuts, grains, vegetables, insects, bird eggs; consumes 3-5 grams per day; can survive without water (sufficient water from food)
Feeding range	Up to 30 metres	Up to 50 metres	Up to 35 metres
Lifespan	9-18 months	9-18 months	9-18 months
Litter size	5-10	7-12	4-12
Reproduction rate	5-6 litters per year (gestation of 23 days)	6 litters per year (gestation of 21-23 days)	11 litters per year (gestation of 20 days)

Key facts for controlling black rats:

Signs of rodent activity in the rafters and ceiling cavities of buildings mean you are likely dealing with black rats. Black rats can be targeted specifically by placing secure bait stations in areas of activity (i.e. along roof beams, rafters and ceiling cavities), routinely monitoring bait intake, and replenishing stations as required.

Rodenticides for black rats:

- Baits containing second-generation anticoagulant rodenticides brodifacoum, bromadiolone, difethialone and flocoumafen are highly effective against black rats.
- Zinc phosphide is highly toxic to all rodents, but its use requires a permit and is generally recommended only during plagues.
- Baits containing the second-generation rodenticide difenacoum, first-generation rodenticides coumatetralyl, diphacinone and warfarin, and the acute toxin cholecalciferol are less effective because repeated feeding is required for a fatal dose.

Key facts for controlling brown rats:

Visible burrows along the edges of sheds are a sign that brown rats are present on your farm. Brown rats can be targeted specifically by placing secure bait stations in areas of activity (shed perimeter, entrances and access points), routinely monitoring bait intake, and replenishing bait as required. Placement of road base, gravel or bitumen around the perimeter of sheds can be an effective way to prevent burrowing (Colvin et al., 1996).

Rodenticides for brown rats:

- Baits containing second-generation anticoagulant rodenticides brodifacoum, bromadiolone, difethialone and flocoumafen are highly effective against brown rats.

- Zinc phosphide is highly toxic to all rodents, but its use requires a permit and is generally recommended only during plagues.
- Baits containing the second-generation rodenticide difenacoum, first-generation rodenticides coumatetralyl, diphacinone and warfarin, and the acute toxin cholecalciferol are less effective because repeated feeding is required for a fatal dose.

Key facts for controlling mice:

It is very difficult to eliminate mice from a poultry operation, given their small size and rapid reproduction. Mice are neophilic, which means they are inquisitive of novel objects and food sources, and will readily eat bait. Place bait stations in areas of known activity, use rodenticide compounds that are effective against mice specifically, routinely monitor bait intake, and replenish bait stations as required.

Rodenticides for mice:

- Effective rodenticides include the second-generation anticoagulants; brodifacoum, bromadiolone, difenacoum, difethialone or flocoumafen.
- Cholecalciferol (vitamin D_3) is also an effective rodenticide that has the added benefit of lower secondary poisoning risk.
- Zinc phosphide is highly effective for controlling mice, but its use requires a permit and is generally recommended only during mouse plagues.
- Coumatetralyl, diphacinone and warfarin are less effective against mice because repeated feeding of bait is required for a fatal dose.

General rodent control strategies (for all species):

If producers are unsure which rodent species they are dealing with or if multiple rodent species are present on-farm, then the following steps will help prevent further rodent colonisation:

- Minimise preferred rodent food sources through secure housing of grain (ideally sealed containers), cleaning up feed spills and removing food scraps and waste from the areas surrounding bird housing sheds.
- Remove piles of rubbish or any materials that might serve as shelter for rodents from predators.
- Rodents will be less likely to move from another shed or location and will be more susceptible to predators if they have to cross exposed ground (Meerberg et al. 2004), so keep grass and weeds cut short around the edges of sheds to minimise rodent migration.
- Place secure bait stations in areas of known rodent activity, routinely monitor bait intake, and replenish as required.
- Don’t place bait stations in areas with birds. Tie baits down securely (using skewers or zip ties) within bait stations to minimise secondary poisoning risk.
- Baits containing the second-generation anticoagulant rodenticides brodifacoum, bromadiolone, difethialone and flocoumafen are effective against all rodent species.
- First-generation anticoagulant rodenticides coumatetralyl, diphacinone and warfarin are generally not recommended because repeated feeding of bait is required for a fatal dose.
- Zinc phosphide is a highly lethal compound, but its use requires a permit and is generally recommended only during plagues.

Bait formulation, housing and palatability

Rodenticide bait formulation
Rodenticides come in many different bait formulations, including paraffin wax blocks, extruded blocks, pelleted bait, grain bait, liquid bait, tracking powders and bait concentrates. For rodenticides to be effective, target rodents must voluntarily ingest sufficient amounts of bait. Therefore, successful control requires the type of bait used to be palatable and enticing to rodents. The features, application, and suitability (for use in poultry operations) of the different bait formulation types is described below.

Grain/pelleted baits
Grain and pelleted baits are the most palatable and widely accepted formulation for rodents because they are similar to preferred natural food sources (grains, nuts, vegetables). However, these bait types are difficult to house securely. Because rodents tend to hoard food, they will often try to remove bait from bait stations to take it to their burrows or nests to eat later. Therefore, bait could potentially be scattered in areas where it may become hazardous to non-target animals, including birds. Consequently, grain and pelleted baits are unsuitable for use in poultry operations because of the higher secondary poisoning risks.

Block rodenticides
The most commonly used bait types – paraffin wax and extruded blocks – are useful in areas with a high level of moisture, which may cause other bait types to clump or spoil. Rats will accept blocks less readily than loose or pelleted grain baits, but their design enables them to be tied down in bait stations using skewers, wire or zip ties. This prevents rats from removing bait from secure bait stations and minimises the risk of secondary poisoning of non-target species. For this reason, extruded and wax blocks are the most favourable bait formulation for poultry operations, provided they are secured in enclosed bait stations in areas where birds or non-target animals do not have access.

Liquid rodenticides
Sodium salts of anticoagulants are available as concentrates that can be mixed with water to create liquid bait. Like most mammals, rats require fresh water to survive, so restricting access to natural sources of water can drive rodents to consume these liquid rodenticides. However, because liquid bait may also be enticing to non-target animals, it must be used carefully so as to prevent non-target animals from accessing it. In poultry operations, the use of liquid bait is generally advised only for internal shed areas during cleanout when birds are absent.

Tracking powders
Tracking powders are powders or dusts containing active concentrations of a rodenticide placed on the ground in areas with high rodent activity. As rodents walk through the powder, it sticks to their fur and paws and is inadvertently consumed during self-grooming. The amount of powder ingested during grooming is likely to be small, therefore the active concentration of tracking powders is much higher than those in consumable bait formulations with the same active compound. Tracking powders can be advantageous in areas with an abundant food supply for rodents and, therefore, where rodents have difficulty accepting ingestible bait formulations, such as wax blocks or liquid concentrates. However, the high active concentration and generally unsecured nature of this baiting method means that its use carries a greater risk of secondary poisoning or contamination (Timm, 1994). Extreme care must be taken to ensure that tracking powders are not placed in areas where they may come into contact with animal feed, human food products or non-target animals. Therefore, there is limited potential for the safe application for tracking powders in poultry operations.

Bait housing
Secure bait housing is essential for the safe and effective use of rodenticides. Enclosed lockable bait stations are the preferred housing method because they protect bait from moisture and dust, provide a secluded area for rodents to feed, and prevent non-target animals from accessing the bait inside. Bait stations should be placed on the ground and in areas of rodent activity and along transit lines, ideally between rodent shelter and food supply. Common practice is to place bait stations at fixed intervals

around the perimeter of bird housing sheds. To prevent secondary poisoning, bait stations should not be placed on the floor in areas where birds have access. However, they can be safely placed in roof cavities, on wall ledges, underneath sheds or any other areas where rodents are active. For detailed information about identifying the activity of rodents, see the 'Target species' section of this review. Users of anticoagulant rodenticides should be aware that detectable residue concentrations of rodenticides can be excreted by baited rodents through faeces; the use of anticoagulants carries an inherent contamination risk.

During periods of high rodent activity, more temporary bait stations can be placed in active areas. Bait stations should be regularly inspected, with bait intake recorded, old bait discarded, and fresh bait distributed. Heightened activity may require more frequent checking of bait stations. Effective baiting strategies depend on the mode of action of the rodenticide. Users must follow specific instructions on product labels. For detailed instructions on handling and user safety, users should refer to the relevant Safety Data Sheet.

In general, first-generation anticoagulant rodenticides can be described as chronic rodenticides because repeated bait feeding is needed to deliver a lethal dose. Therefore, a constant supply of bait and frequent replacement is needed to ensure continuous availability. This technique is known as surplus, or saturation, baiting (Dubock 1984).

Second-generation anticoagulant rodenticides are more potent, so it is possible for target rodents to consume sufficient bait for a lethal dose in a single feed. A comparative assessment of a range of second-generation rodenticides has found that treatment efficacy is directly related to the acute toxicity of the baits (Greaves et al., 1988). Table 14 provides a comparative summary of the amount of feed needed to be eaten for an LD_{50} (lethal dose 50% or median lethal dose; the dose of a compound required to kill half of the members of a tested population over a specified time) for a range of rodenticides against house mice (*Mus musculus*) and Norway/brown rats (*Rattus norvegicus*). Using compounds with a lower feed requirement has the benefit of providing control with comparatively smaller amounts of bait and less labour. The lower amount of bait rodents eat may also reduce levels of residues, potentially lowering the risk of secondary poisoning and contamination (Dubock 1984).

Bait palatability

Contrary to popular belief, rodents, particularly rats, will not voluntarily eat inferior or spoiled food when enticing options are available. Rodenticide efficacy relies on target rodents voluntarily eating sufficient amounts of bait. Therefore, preventing access to preferred food sources (grain) is essential to improving the acceptance of rodenticide bait. Where possible, feed should be housed in secure, sealed containers. For effective control through baiting, users must identify the rodent species they are dealing with (see section on Target species) and identify active compounds that will be effective (Table 14).

Most active rodenticides will be found in many commercial products. Bait manufacturers combine the active ingredients with unique proprietary blends of non-hazardous ingredients to make baits palatable and enticing to rodents. While this review does not endorse the use of specific trade name rodenticides, users can experiment with commercial baits to identify products that target rodents accept more readily. A simple choice feeding can be tested by placing identical amounts of different commercial baits in bait stations where rodents are active, and then monitoring the amount of bait taken to identify palatable products. Rats specifically are neophobic, which means they are suspicious of new objects and novel foods. Therefore, users should be mindful that rats might not accept a new bait for several days.

Rotating different baits might help maintain their palatability and acceptance. Frequent rotation may have the opposite effect, with target rodents constantly suspicious of the novel food items in their environment. There is no scientific evidence to suggest that rotation of bait products will prevent the development of anticoagulant resistance because all anticoagulant compounds share an identical mode of action. The rotation of baits with different chemical modes of action (e.g. anticoagulant to cholecalciferol) could reduce the development of resistance (Buckle and Prescott, 2012).

Traps and glue boards

Trapping is potentially an effective rodent control method, but it is labour intensive and less effective against the large rodent populations on poultry operations. Advantages include not relying on hazardous chemicals with secondary poisoning and contamination risk. They enable users to directly observe effectiveness, and dispose of rodent carcases, which can be reservoirs for disease and odours.

Trap designs include snap traps, wire-mesh cages, funnel cage traps and modified oil drums, each with advantages and disadvantages. Traps are most effective in areas with regular activity and routine travel, which will be unique to the environment, but generally includes areas close to walls or in corners. Leaving traps unset and allowing rodents to take enticing food bait, such as peanut butter or marshmallows, at least once can prevent rodents becoming trap shy.

Glue boards function by causing rodents that travel across them to adhere to the board. Similar to traps, glue boards are most effective in established transit lines and areas with high activity. They are generally more effective for capturing mice because adult rats are large and powerful enough to pull themselves free. Glue boards lose their tackiness if covered by dust or exposed to temperature extremes, therefore they can be left exposed only for short periods of time.

The physical control methods described above can be used to supplement existing methods, but given that many vermin are attracted to poultry operations, they are unlikely to provide sufficient control on their own.

Comparative assessment of commercial rodenticides

Table 14 contains a comparative summary of the toxicity of all active compounds in commercial rodenticides used against house mice (*M. musculus*) and brown/Norway rats (*R. norvegicus*). Most scientific research on the effects of rodenticide compounds have been performed on brown/Norway rats; there is limited information on the toxicity of these compounds in black rats (*R. rattus)*. Given their close biological relationship and the lack of published data, it is reasonable to conclude that the toxicity of various commercial rodenticides will be similar for both breeds.

Feed requirement for LD_{50} refers to the amount of commercial bait containing that active compound that the target rodent will have to consume to ingest a median lethal dose. This is calculated using the range of active concentrations at which active compounds are found in commercial rodenticides, animal bodyweight and species LD_{50} value (from literature). The results in this table assume 20 grams bodyweight and 2–5 grams daily feed requirement for mice, and 320 grams bodyweight and 20–30 grams daily feed requirement for rats.

Against mice, zinc phosphide has the smallest feed requirement, followed by second-generation anticoagulants (brodifacoum, bromadiolone, difenacoum, difethialone and flocoumafen) and cholecalciferol (vitamin D_3). Because first-generation anticoagulants have a relatively high feed requirement, repeat feeding of bait over several days (which is difficult to achieve on-farm) is needed for effective control. Against rats, zinc phosphide and second-generation anticoagulants (except difenacoum) have the lowest feed requirement. The first-generation anticoagulants, cholecalciferol and difenacoum all require repeated feeding of bait for an LD_{50} and are not suitable for rat control.

Liver half-life is the time required for the concentration of a rodenticide to reduce by one half in the target rodent's liver. It influences the level of secondary poisoning and residue risk associated with a particular rodenticide. Zinc phosphide does not accumulate in the tissues of baited rodents, which lowers the risk of secondary poisoning. However, because birds are highly sensitive to zinc phosphide bait too, care should be taken to separate birds from bait sources. Second-generation anticoagulants have a lower feed requirement, but they are highly persistent in the livers of baited rodents. Therefore, their use is associated with higher risk of residue contamination. Producers using anticoagulant compounds should be aware of this risk, and minimise contamination of production areas with the bait and baited rodents. Cholecalciferol persists in the liver and fat tissue of baited rats for up to 81 days

(data not available for mice). However, birds are less susceptible to the metabolites of vitamin D_3 than rodents, which reduces the risk of secondary poisoning.

In summary, no rodenticides are free of risks or drawbacks. Producers are advised to consider their production system, identify the rodent species they encounter, select an appropriate rodenticide, follow instructions for safe application, and devote resources to facility maintenance and hygiene. This will maximise the likelihood of effective rodent control, and minimise the risk of contamination, secondary poisoning and the accumulation of residues. For an in-depth assessment of each commercially available rodenticide, refer to the relevant sections of the rodenticide product manual in the complete version of the literature review (attached).

Table 14: Comparative toxicity summary of APVMA-registered rodenticides against house mice (*Mus musculus*) and Norway/brown rats (*Rattus norvegicus*).

Bait	Mice (*Mus musculus*)			Rats (*Rattus norvegicus*)		
Active	**Feed requirement for LD_{50} (grams of bait)**	**Time to death**	**Liver half-life**	**Feed requirement for LD_{50} (grams of bait)**	**Time to death**	**Liver half-life**
Acute poisons						
Cholecalciferol	Single feed (1.1-3.6 g)	3-21 days	Unknown (birds less susceptible to metabolites)	Repeated feed (18.7 g)	2-11 days	81 days (birds less susceptible to metabolites)
Zinc phosphide	Single feed (0.02-0.05 g)	20 mins: several days (dose dependent)	No accumulation	Single feed (0.35-0.77 g)	20 mins: several days (dose dependent)	No accumulation
First-generation anticoagulants						
Coumatetralyl	Repeated feed (2.5-54 g)	3-21 days	16 days	Repeated feed (0.66-14.3 g)**	3-17 days	55 days
Diphacinone	Repeated feed (56.4 g)	3-21 days	2-4 days	Repeated feed (19.2 g)	3-14 days	3 days
Warfarin	Repeated feed (15-29.9 g)	6-8 days	67 days	Repeated feed (37-74 g)	3-17 days	10-26 days
Second-generation anticoagulants						
Brodifacoum	Single feed (0.16 g)	3-18 days	307 days	Single feed (1.66 g)	3-14 days	114-130 days
Bromadiolone	Single feed (0.4-0.8 g)	3-19 days	28 days	Single feed (3.6-4.8 g)	2-16 days	170 days
Difenacoum	Single feed (0.32 g)	4-22 days	62 days	Multiple feed (11.6-16 g)	4-13 days	120 days
Difethialone	Single feed (0.38-1.03 g)	2-20 days	29 days	Single feed (3.7-6.5 g)	2-16 days	108 days
Flocoumafen	Single feed (0.4-1 g)	4-19 days	94 days	Single feed (1.6-3.6 g)	3-11 days	220 days

**Coumatetralyl bait concentration ranges from 0.37 to 8 g/kg; 8 g/kg products may be lethal for rats in a single feed, all other products require repeated feeding of bait for effective control.

Implications

Rodents are a widespread and persistent issue both for the Australian chicken meat and egg industries. This project directly implicates rodents as a cause of significant levels of farm structural and property damage, and a threat to food safety and food hygiene. The economic burden associated with rodent infestations is difficult to quantify given their insidious nature and hidden impact. The total cost of rodent infestations, which includes structural repairs, feed loss, production loss, disease incidents, energy inefficiencies and the implementation of year-round rodent control programs, is likely to be significant.

In Australian poultry operations, rodent control primarily consists of the use of poison baits, specifically anticoagulant rodenticides. If used appropriately, and with a range of physical management strategies, these compounds can be an effective tool for managing rodents on-farm. But if used inappropriately, the inherent risks associated with these compounds could affect the profitability, productivity and integrity of the Australian chicken meat and egg laying industries. Risks associated with these compounds include the development of resistance in rodent species, secondary poisoning of livestock, wildlife and domestic animals, and the acquisition of residues in the food chain from contamination of animal feed or the farm environment.

Outputs from this project have the potential to improve on-farm rodent management. Potential benefits include better poultry bird health and the prevention of disease transmission from rodents. Reductions in on-farm rodent populations will also reduce structural damage, feed loss and contamination commonly caused by rodents. Appropriate and efficient use of rodenticides in conjunction with physical management strategies, such as rodent habitat disruption and physical exclusion, will reduce the risk of non-target poisoning of livestock, native wildlife species and domestic animals.

Recommendations

Industry information and documentation relating to rodent management in poultry operations needs to be revised to provide producers with accurate and up-to-date information to improve the management of rodents on-farm. The literature review produced from this project, delivers a comprehensive review of scientific literature on available and emerging rodent control products suitable for implementation in chicken meat and layer production systems. This document raises awareness of the advantages, disadvantages, risks and regulatory requirements associated with specific active compounds and provides producers with an objective comparison of all rodenticides currently registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Information is also included relating to target species behaviour and ecology, integrated rodent management strategies and novel and emerging rodent control products. This resource should be made available to Australian poultry producers and practical elements should be published in the next updated versions of the national biosecurity manuals for chicken meat and egg layer production.

From the results of the industry survey, two recommendations are:

- It is strongly recommended that baits be securely fixed inside enclosed bait stations, using either wire, a tie-down or a skewer. Less secure bait housing methods (for example, homemade PVC bait housing, bait placed in brown paper bags or improvised containers) are not recommended because rodents are known to hoard food sources (including bait) and bait that is not securely housed could become scattered around production areas of farms, raising the risk of contamination or secondary poisoning.
- Producers should refer to the instructions of use for particular rodenticide products, and closely monitor and record the level of bait intake and rodent activity at each bait station.

Appendices

Appendix 1: Survey Questionnaire for Layer & Broiler Producers

Industry rodent control survey

Part 1 – Production System:

Q1. What production systems are you running? i.e. Caged, Barn, Free Range for layers; Conventional, Free Range for broilers.

Q2. Does your operation carry any formal certification?

Q3. Do your rodent control strategies/practices differ for each of these production systems? How so?

Q5. Can you provide some indication of the size of your establishment? i.e. number of birds, number of sheds, size of sheds.

Q6. How long have your sheds been in operation? What condition are they in? Are there any unsealed points of entry for rodents to gain access? i.e. open drains, damaged door seals, open hatches, roller doors.

Part 2 – Rodent Observations:

Q1. Do you commonly observe rodents or signs of rodents on your farm? Would you say you have a rodent problem?

Q2. Does this observation change seasonally? Do you have peak or plague seasons?

Q3. Which production areas are rodents observed in? i.e. sheds, feed storage areas, external areas. Are rodents observed in sheds or range areas where birds are housed?

Q4. What rodent species do you predominantly observe? i.e. black/roof rats, brown/Norway rats, mice.

Q5. In the past, have you ever had any feed loss, contamination, structural damage or disease incidents associated with rodents?

Part 3 – Rodent Control Protocols:

Q1. Do you have a documented protocol for rodent control/baiting strategies? i.e. biosecurity manual, grower's manual, company protocol.

Q2. What specific instructions are outlined in this protocol? Please be as detailed as possible (does it advise which type of bait to use? How many bait stations to deploy? How frequently to check these stations? Instructions on facility maintenance and upkeep?)

Part 4 – Rodent Control Products and Services:

Q1. Do you use pest control contractors to assist with rodent control? What service do they provide?

Q2. Do you have any controls in place to prevent rodents from entering specific production areas? i.e. physical barriers, traps, rodent proof seals/walls.

Q3. What rodent control products (rodenticides) do you use? Are they wax blocks, extruded blocks, pellets, tracking powder, liquid? What are the active ingredients in these products?

Q4. Where do you purchase these rodent control products? Chemical supplier, hardware store, pest control contractor?

Q5. Approximately how much rodenticide do you purchase each year?

Q6. Where on your property is surplus rodent bait stored?

Part 5 – Rodent Control Practices:

Q1. What type of bait stations do you use? i.e. commercial enclosed bait stations, handmade from PVC, other.

Q2. How many bait stations do you have in place on your property?

Q3. Where on your property are bait stations placed? i.e. inside/outside sheds, near feed storage areas, external perimeter.

Q4. How are the optimal locations for bait stations determined?

Q5. How much bait is typically placed in bait stations at one time?

Q6. How frequently are bait stations checked and replenished?

Q7. Do you conduct regular searches for and remove rodent carcases on your farm?

Q8. Do you perform supplementary/additional baiting during peak or plague seasons? What does this look like? i.e. more frequent checks, additional bait stations, loose bait in different areas.

Part 6 - Your Thoughts:

Q1. Do you see potential issues with rodenticide use? Detection of residues, development of resistance in rats and mice, secondary poisoning of livestock, wildlife or domestic animals?

Q2. On a scale of 1 (useless) to 10 (very effective) how would you rate your rodent control program?

Thanks for taking the time to complete our survey. Please leave contact details so we can get in touch to clarify your responses:

Name:
Phone number:
Email:

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Appendix 2: A literature review of rodent control for the Australian chicken meat and egg industries

A literature review of rodent control for the Australian chicken meat and egg industries

AgriFutures Chicken Meat

Australian Eggs Limited

SARDI Food Sciences

Alex Howard, David Hamilton, Jessica Jolley

Contents

Foreword

In Australia, rodent control has historically relied on the heavy use of pesticides. In recent years, their use has come under increasing scrutiny, with growing awareness of ethics, efficacy, environmental safety, and best practice use. This document delivers a comprehensive review of scientific literature on available and emerging rodent control products suitable for use in chicken meat and egg (layer) production systems. The aim of this document is to raise awareness of the advantages, disadvantages, risks and regulatory requirements associated with specific active compounds, and to provide producers with an objective comparison of all rodenticides currently registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Also included is information about target species' behaviour and ecology, integrated rodent management strategies, and novel and emerging rodent control products. Note: The listing of any rodenticide or trade name of any rodenticide does not constitute or imply endorsement of that pesticide by the authors. The approved use of rodenticides is dependent on state and federal legislation, which may vary across location and time. Users should refer to the APVMA website (https://apvma.gov.au/) for the most up-to-date information.

The issue

Rodent infestations are a feature of rural Australia, affecting grain growers, intensive livestock industries and rural communities. For Australian poultry farmers (breeders, meat chicken, and layers) in particular, it is a constant/daily battle to keep rodents at bay. Rats (*Rattus norvegicus* and *Rattus rattus*) and, to a lesser extent, mice (*Mus musculus*) are the major offending species.

Rodents pose a major risk to food safety and food hygiene through feed contamination and the ability to transmit disease-causing organisms through their feet, fur, saliva, droppings, urine and blood. The largest rodent-related disease threat specific to poultry health, food safety and farm biosecurity is salmonellosis, an infection caused by the transmission of *Salmonella* bacteria. Rodents also represent a threat to human health through the transmission of zoonotic pathogens (Meerberg et al., 2009). These include various bacteria (for example, *Leptospira* sp., *Borrelia* sp., *Rickettsia* sp.), viruses (for example, hantavirus, tick-borne encephalitis virus, hepatitis E virus) and parasites (such as *Toxoplasma gondii*, *Giardia* sp., *Echinococcus* sp.) (Meerburg et al., 2009). Rodents are also a food source that can attract predators, such as foxes, stray cats, birds of prey or snakes, which in turn may contribute to disease problems or stock loss.

Rodents cause significant damage to farm facilities. They chew through walls to gain access to food, and break down insulation and building materials to take back to their burrows. This compromises the structural integrity of shed walls, floors and ceilings, undermining disease barriers and creating energy inefficiencies that raise operating costs. Rodents also cause a vast amount of damage to wiring, through their gnawing and burrowing. It can lead to equipment malfunctions, power outages and, in severe cases, fires, which can threaten the lives of people and livestock. While there is little published research on the economic cost of rodents to poultry operations, a recent CSIRO survey of Australian pork producers, who encounter similar issues with rodents, estimated the overall cost of rodents was between $10,000 and $250,000 annually per property, depending on the level of rodent activity (Brown and Henry, 2018). This cost included buying bait, time spent checking and replenishing bait stations, and the cost structural damage to farm facilities.

There are numerous rodent control products on the market, many with marketing claims of effective control and rapid action. The only currently available industry resources for producers are the *National Farm Biosecurity Manual for Chicken Growers* (latest version is February 2010, but currently being updated) and the *National Farm Biosecurity Technical Manual for Egg Production* (latest version is April 2015, but currently being updated). These manuals instruct producers to limit rodent access, develop and implement an appropriate rodent control strategy, and implement baiting programs where a risk assessment deems it necessary. Despite recent research advancements, these manuals provide limited information on current products, their effectiveness, availability, implementation and suitability for different situations (for example, normal operations vs plague outbreaks). Therefore, it is difficult for producers to cut through the spin, and objectively compare rodenticides for efficacy, application and level of risk.

The importance of strict biosecurity and holistic approaches to managing rodents has been well documented, but there is a lack of readily available, detailed information on up-to-date rodent control practices and the toxicological effects of various rodent control products in a format that is understandable, easy-to-use and relevant to Australian poultry producers. Other countries have identified the need for industry guidelines on anticoagulant rodenticide use, e.g. the *UK Rodent Eradication Best Practice Toolkit: Use of Anticoagulant Rodenticides* (Annex 5: Use of Anticoagulant Rodenticides: Risk management, consents & best practice protocols) (Thomas et al., 2017) and the European Commission's *Risk Mitigation Measures for Anticoagulant Rodenticides as Biocidal Products Final Report* (October 2014). Because these documents are specific to the United Kingdom and Europe, they cannot be directly applied to Australia, which has a very different landscape and climate.

Studies of rodent control programs in international pig and poultry enterprises have identified several risks associated with the incorrect use of rodenticides. These include failure to reduce target rodent populations (León et al., 2009), the development of rodenticide-resistant rat populations (Berny et al., 2014; Meerburg et al., 2014) and the higher risk of non-target poisoning of animals and livestock (Damin-Pernik et al., 2016).

This document delivers a comprehensive review of scientific literature and relevant non-published technical material that relates to available and emerging rodent control products suitable for use in chicken meat and egg (layer) production systems. It aims to provide an objective assessment of all rodenticides currently registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA). Also included is information relating to target species' behaviour and ecology, integrated rodent management strategies, and novel and emerging rodent control products. This information will help the Australian chicken meat industry body and the Australian egg industry body understand the potential risks associated with current rodent control programs. It also provides key product information that can be used to improve on-farm rodent management.

Target species

There are three main rodent pest species relevant to poultry operations in Australia: the black rat (*Rattus rattus*), Norway rat (*Rattus norvegicus*) and house mouse (*Mus musculus*). They are known as commensal rodent species because they benefit from establishing populations alongside man-made infrastructure (Buckle and Smith, 2015). Each rodent species has a unique set of physical features and behavioural adaptations that need to be considered when designing a rodent control program. Table 15 summarises the physical features and behavioural characteristics of each rodent species. Correctly identifying the offending rodent species on-farm will allow for targeted rodent control strategies, increasing the likelihood that rodent control efforts will succeed.

Table 15: Comparison of physical features and behavioural characteristics of *Rattus rattus*, *Rattus norvegicus* and *Mus musculus*, the three main rodent pest species observed in poultry operations in Australia.

Scientific name	*Rattus rattus*	*Rattus norvegicus*	*Mus musculus*
Common names	Black rat, roof rat, ship rat, fruit rat	Norway rat, brown rat, sewer rat	House mouse, field mouse
Image			
Adult size	200-340 grams	200-480 grams	15-25 grams
Length (head+body)	150-220 mm	180-255 mm	60-90 mm
Length (tail)	180-250 mm	150-215 mm	80-100 mm
Fur & colour	Smooth and soft; black/grey/brown	Rough and shaggy; grey/brown	Sleek; brown/grey
Descriptive features	Thin, large and hairless ears; large eyes; pointed snout	Thick, opaque and fine-haired ears; small eyes; blunt snout	Large ears relative to body; small eyes; pointed snout
Droppings	Scattered; pointed ends  7-14mm	Grouped; rounded ends  14-19mm	Scattered; pointed ends  4-7mm
Habitat and behaviour	Nests in walls, roof cavities, vines and trees; agile climber; somewhat neophobic (avoids novel objects and new foods)	Nests in burrows; can climb but not agile; neophobic (avoids novel objects and new foods); hoards food for future consumption (including bait)	Nests in burrows or crevices; neophilic (inquisitive of novel objects and will try new food); good climber

Preferred diet	Omnivore: prefers fruits, nuts, grains and vegetables; will eat human waste, insects, small mammals, bird eggs and nestlings; consumes 25-30 grams per day; needs a source of fresh water	Omnivore: prefers fruits, nuts, grains and vegetables; will eat human waste, insects, small mammals, bird eggs and nestlings; more likely to eat meat than *Rattus rattus*; consumes 30 grams per day; needs a source of fresh water	Omnivore: will eat fruits, nuts, grains, vegetables, insects, bird eggs; consumes 3-5 grams per day; can survive without water (sufficient water from food)
Feeding range	Up to 30 metres	Up to 50 metres	Up to 35 metres
Lifespan	9-18 months	9-18 months	9-18 months
Litter size	5-10	7-12	4-12
Reproduction rate	5-6 litters per year (gestation of 23 days)	6 litters per year (gestation of 21-23 days)	11 litters per year (gestation of 20 days)

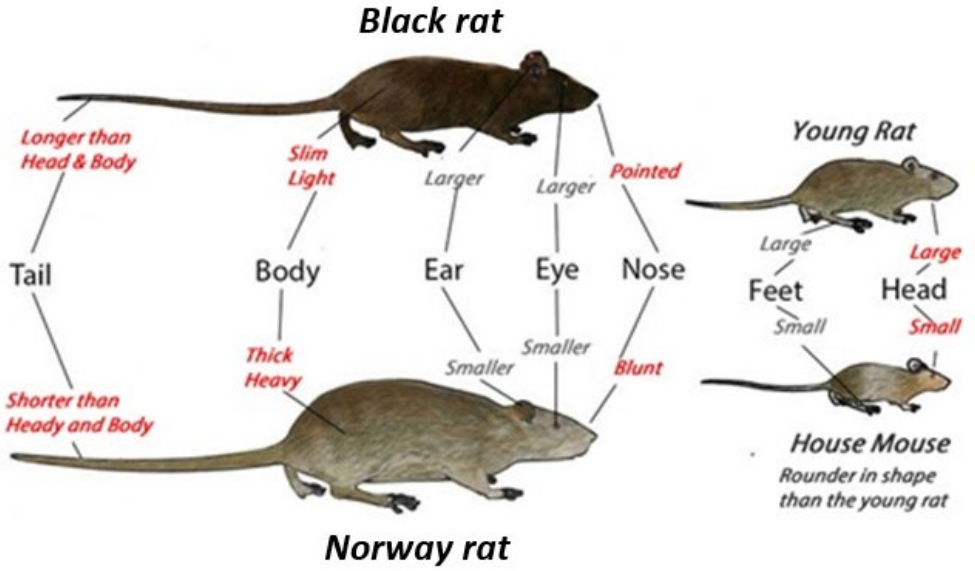

Image 1: Comparison of the physical features of the black rat (*Rattus rattus*), Norway rat (*Rattus norvegicus*) and house mouse (*Mus musculus*) to help with the identification of rodents on-farm.

Black rat (*Rattus rattus*)

Physical description

The black rat (*Rattus rattus*), also known as the roof rat, ship rat or fruit rat, is a pest rodent species endemic to much of coastal Australia. They commonly inhabit urban and agricultural environments due to the availability of food, water and shelter.

Image 2: Black rats feeding; note the key identifying features, which include the large ears and pointed snouts.

Despite the name, black rats can be brown, grey or black in colour; their fur is smooth and soft in appearance. They are visually distinguishable from Norway rats because of their smaller stature, longer tail relative to body, hairless ears, large eyes and pointed snout (see Images 1-3).

Behavioural features

Black rats are active and agile climbers, often found nesting in roof voids and ceiling cavities. They dig burrows from time to time, although not as commonly as Norway rats. The observation of black rat droppings, which are uniquely banana shaped and typically scattered within roof cavities, is one way to identify a black rat incursion without visual observation of the rodents themselves.

While not as intelligent as Norway rats, black rats display similar neophobic behaviours. This means they are reluctant to investigate novel objects (i.e. bait stations, traps) or try new sources of food (bait) in their environment. Because black rats feed mostly at night, daytime observations are a sign of a high local population that is driving competition for available food.

Diet

Black rats have an omnivorous diet consisting predominantly of fruits, nuts, grains and vegetables. They will also eat food scraps, human waste, insects and bird eggs. An adult-sized black rat will eat 25-30 grams of food per day, receiving most of their daily water intake from the moisture in their food, although they do need a source of fresh water to survive.

Black rats forage mainly at night, ranging up to 30 metres from their nest in search for food. If given a choice, black rats will selectively eat animal feed instead of bait. Therefore, limiting the availability of food and water is an essential component of any rodent control program.

Lifespan and reproduction

Black rats have a natural lifespan of 9-18 months. They reproduce rapidly, producing 5-6 litters, each containing 5-10 rats each year. One female black rat can spawn up to 60 offspring in a calendar year. If not managed effectively, black rat populations can escalate quickly, increasing the likelihood and severity of structural damage, feed losses and disease.

Image 3: Black rat on ceiling beam; note the tail length (longer than body) and slender build.

Key facts for controlling black rats:

- Signs of rodent activity in the rafters and ceiling cavities of buildings mean you are likely dealing with black rats.

- Target black rats specifically by placing secure bait stations in areas of activity (i.e. along roof beams, rafters and ceiling cavities), routinely monitoring bait intake, and replenishing stations as required.

Rodenticides for black rats:

- Baits containing second-generation rodenticides brodifacoum, bromadiolone, difethialone and flocoumafen are highly effective against black rats.
- Zinc phosphide is highly toxic to all rodents, but its use requires a permit and is generally recommended only during plagues.
- Baits containing the second-generation rodenticide difenacoum, first-generation rodenticides coumatetralyl, diphacinone and warfarin, and the acute toxin cholecalciferol are less effective because repeated feeding is required for a fatal dose.
- For detailed information on these compounds, see the Rodenticide product manual in this review.

Norway rat (*Rattus norvegicus*)

Physical description

The Norway rat (*R. norvegicus*), also known as a brown or sewer rat, is a pest rodent species predominantly found along the coastal regions of southern and eastern Australia. Norway rats are common in urban and agricultural centres because of the availability of food and water as well as the shelter provided away from predators.

Image 4: Norway rat; note the stocky body, smaller ears and eyes, and more rounded snout.

Norway rats are visibly distinguishable from black rats because of their slightly larger size, thicker stature, blunt snout, small eyes, and shorter tail relative to the head and body (see Image 1, Image 4 and Image 5). Their fur is rough and shaggy in appearance, and varies in colour from brown to grey. Norway rat droppings, which are uniquely capsule shaped and are laid in groups, can also be used to identify its on-farm presence.

Behavioural features

Norway rats are highly intelligent animals, displaying risk-averse and neophobic behaviours, often waiting several days before investigating novel objects in their surrounding environment (i.e. bait stations, traps, new food sources). Norway rats feed mostly at night, emerging from their burrows at sunset and ranging up to 50 metres in search of food. Observations of rat activity during the day are a sign of a high local population that is driving competition for available food.

Image 5: Norway rat; note the tail length (shorter than body) and rounded snout.

Norway rats are poor climbers and are unlikely to be found in roof cavities. Instead, they build burrow systems underground, often along the edges of poultry sheds, where they build nests from scavenged materials and hoard food (including bait). This can result in bait being removed from bait stations and scattered around the farm. Therefore, it is strongly recommended that baits are securely fixed inside bait stations, with wire, a tie-down or a skewer.

Diet

Norway rats have an omnivorous diet, typically consisting of fruit, nuts, grains and vegetables. They will also eat human waste, insects, small mammals, bird eggs and nestlings. Norway rats can eat up to 30 grams of food per day, and will get most of their water from the moisture in their food, although they need a source of fresh water to survive. If given a choice, rats will selectively eat feed instead of bait. Therefore, minimising access to food and water is an essential component of any rodent control program.

Lifespan and reproduction

Norway rats have a lifespan of 9-18 months. They reproduce rapidly, with 6 litters consisting of 7-12 rats produced each year. One Norway rat breeding pair can spawn more than 70 offspring in a calendar year. If not managed correctly, Norway rat populations can quickly escalate, increasing the likelihood of structural damage, feed losses and disease incidents.

Key facts for controlling Norway rats:

- Visible burrows along the edges of sheds are a sign that Norway rats are present on your farm (Image 6).
- Target Norway rats specifically by placing secure bait stations in areas of activity (shed perimeter, entrances and access points), routinely monitoring bait intake, and replenishing bait as required.
- Placing road base, gravel or bitumen around the perimeter of sheds (Image 6) can be an effective way to prevent burrowing (Colvin et al., 1996).

Rodenticides for Norway rats:

- Baits containing second-generation rodenticides brodifacoum, bromadiolone, difethialone and flocoumafen are highly effective against Norway rats.
- Zinc phosphide is highly toxic to all rodents, but its use requires a permit and is generally recommended only during plagues.
- Baits containing the second-generation rodenticide difenacoum, first-generation rodenticides coumatetralyl, diphacinone and warfarin, and the acute toxin cholecalciferol are less effective because repeated feeding is required for a fatal dose.

Image 6: Norway rat burrows along the edges of a structure (left); road base gravel laid down to prevent burrowing (right) (Brown and Henry, 2018).

House mouse (*Mus musculus*)

Physical description

The common house mouse (*Mus musculus*) is the smallest pest rodent in Australia. Mice are widely distributed throughout central and coastal Australia. They are physically distinguishable from other rodents because they are smaller. Adult mice are 120-200 mm in length, with a scaly tail roughly the same length as their head and body. They have sleek fur that can be yellowish brown to grey in colour on their back, and white, grey or pale yellow colouring underneath. Mice have large ears relative to their body, and a small head with a pointed snout and bulging eyes (see Image 1 and Image 7).

Image 7: House mouse; note the distinctive large ears, small feet and head.

Behavioural features

Mice create nests out of scavenged materials in shallow burrows or natural hollows and crevices. They are good climbers, and can easily fit through small holes and gaps, making it difficult to prevent their entry to poultry sheds. Mice are most active at night, emerging from their burrows at sunset and ranging up to 35 metres exploring for food. Visual observations of mice during the day is a clear sign of a significant local mouse population that is creating more competition for food.

Diet

Mice have an omnivorous diet consisting mainly of fruits, nuts, grains and vegetables. They eat 3-5 grams of food per day and can survive without water (they receive sufficient intake through food). Mice are neophilic, meaning that they are inquisitive of novel objects and food sources, and will readily eat bait. This contrasts with the neophobic and novel avoidance behaviour of black and Norway rats.

Lifespan and reproduction

Mice have a lifespan of 9-18 months. They are prolific breeders, with juveniles reaching sexual maturity at just two months of age. They produce 11 litters a year, each with 4-12 pups. This means that a single breeding pair is capable of producing 130 offspring over a 12-month period, each of which will begin to reproduce 8 weeks after they are born (Singleton et al., 2005). If left unchecked, mice populations can exceed 2000 animals per hectare, causing significant operational disruptions and severe financial consequences (Saunders, 1983).

Key facts for controlling mice:

- It is very difficult to eliminate mice from a poultry operation, given their small size and prolific reproduction.
- For poultry operations, mice are typically little more than a nuisance, but in plagues they can cause significant damage.
- Exploit their neophilic behaviour by placing secure bait stations in areas of known activity, routinely monitoring bait intake and replenishing stations as required.

Rodenticides for mice:

- Effective rodenticides for mice include the second-generation anticoagulants: brodifacoum, bromadiolone, difenacoum, difethialone or flocoumafen.
- Cholecalciferol (vitamin D_3) is also an effective rodenticide that has the added benefit of a reduced secondary poisoning risk.

- Zinc phosphide is highly effective for controlling mice, but its use requires a permit and is generally recommended only during mouse plagues.
- Coumatetralyl, diphacinone and warfarin are less effective against mice because repeated feeding of bait is required for a fatal dose.
- For detailed information on these compounds, see the Rodenticide product manual section of this review.

General rodent control strategies (for all species)

If you are unsure which rodent species you are dealing with or if you have multiple rodent species on your farm, then the following steps will help prevent further rodent colonisation:

- Minimise preferred rodent food sources by securely housing grain (ideally, sealed containers), cleaning up feed spills, and removing food scraps and waste from the areas around bird housing sheds.
- Remove piles of rubbish or any materials that might serve as shelter for rodents from predators.
- Rodents will be less likely to move from another shed or location and will be more susceptible to predators if they are required to cross exposed ground (Meerberg et al. 2004), so keep grass and weeds cut short around the edges of sheds to minimise rodent migration.
- Place secure bait stations in areas of known activity, routinely monitor bait intake and replenish as required.
- Don't place bait stations in areas with birds; tie baits down securely (using skewers or zip ties) in bait stations to minimise secondary poisoning risk.
- Baits containing the second-generation anticoagulant rodenticides of brodifacoum, bromadiolone, difethialone and flocoumafen are effective against all rodent species.
- First-generation anticoagulant rodenticides coumatetralyl, diphacinone and warfarin are generally not recommended because repeated feeding of bait is required for a fatal dose.
- Zinc phosphide is a highly lethal compound, but its use requires a permit and is generally recommended only during plagues.

Rodenticide product manual

Structure of the manual

Rodenticide active compounds are referred to by their common chemical names. Chemicals are grouped according to their mode of action, either acute poisons, anticoagulants (first-generation and second-generation), novel and emerging compounds.

The information presented for each chemical is outlined below:

Chemical name: The common name of the chemical.

Other names: Other names or synonyms used to describe the chemical.

Development and use: Description of the history of the chemical from its development through to first applications as a rodenticide, and a summary of how the chemical is currently used in Australia. Readers should always check up-to-date legislation because regulations for chemical use may change frequently.

Mode of action: Description of the physiological or biochemical effect of the chemical on animals, including symptoms, metabolism, persistence and excretion.

Time to death: The time taken for the target animal to die after consuming a lethal dose of the chemical.

Evidence of resistance: Scientific evidence of the ability of target animals to withstand exposure to the chemical that would normally be lethal to most animals of that species. This usually implies that genetic differences have developed within a specific animal population.

APVMA-registered products containing this chemical: A list of rodenticide products containing the chemical registered by the Australian Pesticides and Veterinary Medicines Authority (APVMA) and listed on the Public Chemical Registration Information System (PubCRIS) database.

Available formulation: A list of bait formulation types available for the chemical.

Acute toxicity: Oral median lethal dose (LD_{50}) values provide a guide to the sensitivity of different rodent species (house mice and brown/Norway rats) to the chemical. LD_{50} values are calculated from laboratory feeding trials where a range of factors may influence the toxicity of a chemical, including the age, sex and strain of the experimental animals. These values are, therefore, highly variable and should be used only as a rough guide. The total amount of the chemical required to be consumed to kill an average-sized animal provides another comparison of the relative toxicity of different products and chemicals.

Poison schedule and regulatory requirements: The classification of the chemical according to the Australian Poisons Schedules using the criteria in the *Standard for the Uniform Scheduling of Drugs and Poisons*. Refer to the Appendix for a description of these schedules. Please note that the APVMA may declare certain products as 'restricted chemical products' if special training, and/or other requirements are needed for handling or using the chemical. These designated products can be used only by an 'Authorised Person', who is determined by the relevant state or territory authority. Readers should always check up-to-date legislation because regulations for chemical use may change frequently.

Handling, storage and user safety: A list of procedures needed for handling, storage and safe use of the chemical.

References: A list of all the literature cited for each chemical. These papers may be useful for readers who want to seek more detailed information.

Bait formulation, housing and palatability

Rodenticide bait formulation
Rodenticides come in many different bait formulations, including paraffin wax blocks, extruded blocks, pelleted bait, grain bait, liquid bait, tracking powders and bait concentrates. For them to be effective, target rodents must be voluntarily ingest sufficient amounts of bait. Therefore, successful control requires the type of bait used to be palatable and enticing to rodents. The features, application and suitability (for use in poultry operations) of the different bait formulation types are described below.

Grain/pelleted baits
Grain and pelleted baits are the most palatable and widely accepted formulation for rodents because they are similar to preferred natural food sources (grains, nuts, vegetables). However, these bait types are difficult to house securely. Because rodents tend to hoard food, they will often try to remove bait from bait stations to take it to their burrows or nests to eat later. This can potentially cause bait to be scattered in areas where it may become hazardous to non-target animals, including birds. Consequently, because of the higher secondary poisoning risks associated with grain and pelleted baits, they are unsuitable for use in poultry operations.

Block rodenticides
The most commonly used bait types are paraffin wax and extruded blocks. They are useful in areas with a high level of moisture, which may cause other bait types to clump or spoil. Rats will accept blocks less readily than loose or pelleted grain baits, but their design enables them to be tied down in bait stations with skewers, wire or zip ties. This prevents rats from removing bait from secure bait stations and minimises the risk of secondary poisoning of non-target species. For this reason, extruded and wax blocks are the most favourable bait formulation in poultry operations, provided they are securely housed in enclosed bait stations in areas that birds or non-target animals cannot access.

Liquid rodenticides
Sodium salts of anticoagulants are available as concentrates that can be mixed with water to create liquid bait. Like most mammals, rats need fresh water to survive, so restricting access to natural sources of water can drive rodents to consume these liquid rodenticides. However, liquid bait may also be enticing to non-target animals, therefore this bait formulation must be used carefully to prevent non-target animals from accessing it. In poultry operations, the use of liquid bait is generally advised only for internal shed areas during cleanout when birds are absent.

Tracking powders
Tracking powders are powders or dusts containing active concentrations of a rodenticide placed on the ground where rodents are highly activity. As rodents walk through the powder, it sticks to their fur and paws, and is inadvertently consumed during self-grooming. The amount of powder ingested during grooming is likely to be small, therefore the active concentration of tracking powders is much higher than in consumable bait formulations with the same active compound. Tracking powders can be advantageous in environments with an abundant food supply for rodents and, therefore, where rodents have difficulty accepting ingestible bait formulations, such as wax blocks or liquid concentrates. However, the high active concentration and generally unsecured nature of tracking powders means that using it carries a greater risk of secondary poisoning or contamination (Timm, 1994). Extreme care must be taken to ensure that tracking powders are not placed in areas where they may come into contact with animal feed, human food products or non-target animals. Therefore, there is limited potential for the safe use for tracking powders in poultry operations.

Bait housing
Secure bait housing is essential for the safe and effective use of rodenticides. Enclosed lockable bait stations are preferred because they protect bait from moisture and dust, provide a secluded area for rodents to feed, and prevent non-target animals from accessing the bait. Bait stations should be placed on the ground and in areas of rodent activity and along transit lines, ideally between rodent shelter and food supply. Common practice is for bait stations at fixed intervals around the perimeter of bird housing

sheds. To prevent secondary poisoning, bait stations should not be placed on floor areas where birds have access, but they can be safely placed in roof cavities, on wall ledges, underneath sheds or any other areas where rodents are active. For detailed information about identifying the activity of rodents, see the 'Target species' section. Users of anticoagulant rodenticides should be aware that because detectable residue concentrations of rodenticides can be excreted by baited rodents through faeces, the use of anticoagulants has an inherent contamination risk.

Temporary bait stations can be placed in areas where rodents are more active. They should be regularly inspected, with bait intake recorded, old bait discarded, and fresh bait distributed. Heightened activity may require more frequent checking of bait stations. The effectiveness of baiting strategies depends on the mode of action of the type of rodenticide. Users should follow instructions on product labels. For detailed instructions on handling and user safety, refer the relevant Safety Data Sheet for each product.

In general, first-generation anticoagulant rodenticides can be described as chronic rodenticides because repeated feeding is needed to deliver a lethal dose. This characteristic requires a constant supply of bait and frequent replacement, a technique known as surplus, or saturation, baiting (Dubock 1984).

Second-generation anticoagulant rodenticides are more potent, so it is possible for target rodents to consume sufficient bait for a lethal dose in a single feed. A comparative assessment of a range of second-generation rodenticides found that efficacy is directly related to the acute toxicity of the baits (Greaves et al., 1988). Table 16 provides a comparative summary of the amount of feed required to be consumed for an LD_{50} for a range of rodenticides against house mice (*Mus musculus*) and Norway/brown rats (*Rattus norvegicus*). The use of compounds with a lower feed requirement provides control with comparatively smaller amounts of bait and less labour. When rodents eat less bait, lower levels of residues could reduce the risk of secondary poisoning and contamination (Dubock 1984).

Bait palatability

Contrary to popular belief, rodents, particularly rats, will not voluntarily eat inferior or spoiled food when enticing options are available. Rodenticide efficacy relies on target rodents voluntarily eating sufficient amounts of bait. Therefore, preventing access to preferred food sources (grain) is essential to improving the acceptance of rodenticide bait. Where possible, feed should be housed in secure, sealed containers. For effective control through baiting, users must identify the rodent species they are dealing with (see section on Target species) and identify active compounds that will be effective (Table 16).

Most active rodenticides will be found in many commercial products. Bait manufacturers combine the active ingredients with unique proprietary blends of non-hazardous ingredients to make baits palatable and enticing to rodents. While this review does not endorse the use of specific trade name rodenticides, users can experiment with commercial baits to identify products that target rodents accept more readily. A simple choice of feeding can be tested by placing identical amounts of different commercial baits in bait stations in areas where rodents are active and then monitoring the amount of bait taken to identify palatable products. Rats specifically are neophobic, which means they are suspicious of new objects and novel foods. Therefore, users should be mindful that rats might not accept a new bait for several days.

Rotating different baits might help maintain their palatability and acceptance. Frequent rotation may have the opposite effect, with target rodents constantly suspicious of the novel food items in their environment. There is no scientific evidence to suggest that the rotation of bait products will prevent the development of anticoagulant resistance because all anticoagulant compounds share an identical mode of action. The rotation of baits with different chemical modes of action (e.g., anticoagulant to cholecalciferol) could reduce the development of resistance (Buckle and Prescott, 2012).

Traps and glue boards

Trapping is a potentially effective rodent control method, but it is labour intensive and less effective against the large rodent populations that may be present on poultry operations. Advantages include not relying on hazardous chemicals with secondary poisoning and contamination risk. Traps enable users

to directly observe effectiveness and to dispose of rodent carcases, which can be reservoirs for disease and odours.

Different trap designs include snap traps, wire-mesh cages, funnel cage traps and modified oil drums, each with advantages and disadvantages. Traps are most effective in areas with regular activity and routine travel, but generally includes areas close to walls or in corners. Leaving traps unset and allowing rodents to take enticing food bait, such as peanut butter or marshmallows, at least once can prevent rodents becoming trap shy.

Glue boards function by causing rodents that travel across them to adhere to the board. Similar to traps, glue boards are most effective in established transit lines and areas with high rodent activity. They are generally more effective for capturing mice because adult rats are large and powerful enough to pull themselves free. Glue boards lose their tackiness if covered by dust or exposed to temperature extremes, therefore they can be left exposed only for short periods of time.

The physical control methods described above can be used to supplement existing rodent control programs, but given the level of vermin attracted to poultry operations, they are unlikely to provide a sufficient level of control on their own.

Comparative assessment of commercial rodenticides

Table 16 contains a comparative summary of the toxicity of all active compounds found in commercial rodenticides for use against house mice (*M. musculus*) and brown/Norway rats (*R. norvegicus*). While most scientific research on the effects of rodenticide compounds has been performed on brown/Norway rats, there is limited information on the toxicity of these compounds in black rats (*R. rattus)*. Given their close biological relationship and the lack of published data, it is reasonable to conclude that the toxicity of various commercial rodenticides will be similar for both breeds.

Feed requirement for LD_{50} refers to the amount of commercial bait containing that active compound that the target rodent will have to eat to ingest a median lethal dose. It is calculated using the range of active concentrations at which active compounds are found in commercial rodenticides, animal bodyweight and species LD_{50} value (from literature). The results in this table assume 20 grams bodyweight and 2-5 grams daily feed requirement for mice, and 320 grams bodyweight and 20-30 grams daily feed requirement for rats.

Against mice, zinc phosphide has the smallest feed requirement, followed by second-generation anticoagulants (brodifacoum, bromadiolone, difenacoum, difethialone and flocoumafen) and cholecalciferol (vitamin D_3). First-generation anticoagulants have a relatively high feed requirement. Repeat bait feeding over several days (difficult to achieve on-farm) is needed for effective control. Against rats, zinc phosphide and second-generation anticoagulants (except difenacoum) have the lowest feed requirement. The first-generation anticoagulants, cholecalciferol and difenacoum all require repeated feeding of bait for an LD_{50} and are not suitable for controlling rats.

Liver half-life is the time required for the concentration of a rodenticide to reduce by one half in the liver of a target rodent. It influences the level of secondary poisoning and residue risk associated with a particular rodenticide. Zinc phosphide does not accumulate in the tissues of baited rodents, which reduces the risk of secondary poisoning risk. However, because birds are highly sensitive to zinc phosphide bait too, care should be taken to separate birds from bait sources. Second-generation anticoagulants have a lower feed requirement, but they are highly persistent in the livers of baited rodents. Therefore, their use is associated with a higher risk of residue contamination. Producers using anticoagulant compounds should be aware of this risk, and should minimise contamination of production areas with the bait and baited rodents. Cholecalciferol persists in the liver and fat tissue of baited rats for up to 81 days (data not available for mice). However, birds are less susceptible to the metabolites of vitamin D_3 than rodents, which reduces the risk of secondary poisoning.

In summary, there are no rodenticides that are free of risks or drawbacks. Producers should consider their production system, identify the rodent species they encounter, select an appropriate rodenticide, follow instructions for safe use, and devote resources to facility maintenance and hygiene. This will maximise the likelihood of effective rodent control and minimise the risk of contamination, secondary poisoning and the accumulation of residues. For an in-depth assessment of each commercially available rodenticide, refer to the relevant sections below.

Table 16: Comparative toxicity summary of APVMA-registered rodenticides against house mice (*Mus musculus*) and Norway/brown rats (*Rattus norvegicus*).

Bait	Mice (*Mus musculus*)			Rats (*Rattus norvegicus*)		
Active	**Feed requirement for LD_{50} (grams of bait)**	**Time to death**	**Liver half-life**	**Feed requirement for LD_{50} (grams of bait)**	**Time to death**	**Liver half-life**
Acute poisons						
Cholecalciferol	Single feed (1.1-3.6 g)	3-21 days	Unknown (birds less susceptible to metabolites)	Repeated feed (18.7 g)	2-11 days	81 days (birds less susceptible to metabolites)
Zinc phosphide	Single feed (0.02-0.05 g)	20 mins: several days (dose dependent)	No accumulation	Single feed (0.35-0.77 g)	20 mins: several days (dose dependent)	No accumulation
First-generation anticoagulants						
Coumatetralyl	Repeated feed (2.5-54 g)	3-21 days	16 days	Repeated feed (0.66-14.3 g)**	3-17 days	55 days
Diphacinone	Repeated feed (56.4 g)	3-21 days	2-4 days	Repeated feed (19.2 g)	3-14 days	3 days
Warfarin	Repeated feed (15-29.9 g)	6-8 days	67 days	Repeated feed (37-74 g)	3-17 days	10-26 days
Second-generation anticoagulants						
Brodifacoum	Single feed (0.16 g)	3-18 days	307 days	Single feed (1.66 g)	3-14 days	114-130 days
Bromadiolone	Single feed (0.4-0.8 g)	3-19 days	28 days	Single feed (3.6-4.8 g)	2-16 days	170 days
Difenacoum	Single feed (0.32 g)	4-22 days	62 days	Multiple feed (11.6-16 g)	4-13 days	120 days
Difethialone	Single feed (0.38-1.03 g)	2-20 days	29 days	Single feed (3.7-6.5 g)	2-16 days	108 days
Flocoumafen	Single feed (0.4-1 g)	4-19 days	94 days	Single feed (1.6-3.6 g)	3-11 days	220 days

**Coumatetralyl bait concentration ranges from 0.37-8 g/kg, 8 g/kg products may be lethal for rats in a single feed, all other products require repeated feeding of bait for effective control.

Acute poisons

Acute poisons, as their name suggests, are fast-acting, single-dose toxicants that produce symptoms in rodents very rapidly. While these properties makes them highly effective exterminating agents, rodent behaviour is such that individuals encountering new food for the first time will test it, and not take a substantial quantity for hours, or even days (Buckle et al., 1987). Because rodents are neophobic, they can rapidly develop bait avoidance towards acute poisons, thereby jeopardising a key component of an on-farm rodent control strategy. This is why these compounds are generally most effective when used in short rotation.

CHOLECALCIFEROL

Other names: Vitamin D_3, activated 7-dehydricholesterol

Development and use

Cholecalciferol is produced industrially for use in vitamin supplements and to fortify foods. In the 1970s, rodents were found to be more susceptible to high doses than other animal species and, as a result, cholecalciferol was used in rodenticide products combined with warfarin and by itself (Lund, 1977). It has been used to control rodents in the USA since the 1990s (Witmer et al., 1995) and to control brushtail possums in New Zealand since 1995 (Eason and Wickstrom, 2001).

In Australia, cholecalciferol is used to control rats and mice, particularly anticoagulant-resistant strains. For poultry operations, it can be used in and around structures and along perimeter fence lines. Despite its lower risk of contamination and residues, its use is not advised in ranging areas or inside bird housing sheds (BASF 2018).

Mode of action

Within 14-48 hours, poisoned rodents stop eating, and become lethargic, weak, dehydrated and anorexic. Cholecalciferol poisoning causes hypercalcemia (excessive blood calcium levels), which causes calcification of blood vessels, soft tissues and organs. Death can occur from any of the following causes or a combination: kidney, heart or respiratory failure; or haemorrhaging from the calcification of blood vessels and internal organs (Dorman and Beasley, 1989; Peterson et al., 1991).

In rodents, death can occur from a single large dose or multiple smaller doses in which the compound accumulates a lethal dose faster than it is metabolised (see Acute toxicity). Cholecalciferol is metabolised in the liver and kidneys, producing calcitriol, the most active form of vitamin D_3 (Dorman and Beasley, 1989). Sub-lethal doses of cholecalciferol and its metabolites persist in the adipose tissue (fat) of rats, with a half-life of 81 days (Brouwer et al., 1998). Because birds are less susceptible to cholecalciferol than rodents (McLeod and Saunders, 2013), they are a minor secondary poisoning risk. Dead or dying rodents should still be cleared from production areas as soon as possible to prevent disease transmission.

Time to death:

- Rats: 2-11 days (Greaves et al., 1974 & Lund, 1974)
- Mice: 3-21 days (Hatch and Lanflamme, 1989)

Evidence of resistance

There is no evidence of resistance.

APVMA-registered products containing cholecalciferol:

Selontra® (0.75 g/kg), Rampage® (0.75 g/kg)

Available formulation:

- Pellet bait
- Soft bait

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	42.5-136.4 mg/kg	20 g	1.1-3.6 g*	Marshall, 1984
Norway rat	43.6 mg/kg	320 g	18.7 g*	Marshall, 1984

*Calculated using a bait concentration of 0.75 g/kg

The table above shows the oral median lethal dose (LD_{50}) of cholecalciferol for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight of 320 grams) will eat about 20-30 grams of food daily; an adult mouse (bodyweight of 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Cholecalciferol rodenticides have a standard active concentration of (0.75 g/kg). Therefore, 18.7 grams of bait would be considered a lethal dose for rats and 1.1-3.6 grams of bait lethal for mice. For both species, this is within the daily food requirement but on-farm, where rodents have other food sources, repeated bait feeding is likely to be needed to ensure effective control.

Poison schedule and regulatory requirements

Cholecalciferol is classified as a Schedule 7 Dangerous Poison and is available only to specialised or authorised users. Regulations restricting their availability, possession, storage or use may apply. Please check with your state health authority before purchasing.

Handling, storage and user safety

Bait should be securely stored in its original container in a cool, well-ventilated area, out of direct sunlight and away from sources of heat.

Disposable gloves are recommended when using products containing cholecalciferol. Avoid contact with eyes and skin; wash hands, arms and face thoroughly with soap and water after use.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet.

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ZINC PHOSPHIDE

Development and use

Zinc phosphide is an inorganic chemical compound first used as a rodenticide in Italy 1911. It became popular in the 1930s in Europe and was introduced in the USA in 1943. Zinc phosphide was registered in Australia in 1997 (Caughley et al., 1998). Today it is the one of the few acute poisons still used for the control of pest rodents because alpha-chloralose, phosphorus and strychnine have been phased out (McLeod and Saunders, 2013). It is mainly used to control mice populations in broadacre crops, but it can also be used to control rat populations in specific circumstances (typically for plague incursions).

Mode of action

When ingested, the bait reacts with stomach acids to produce poisonous phosphine gas, causing central nervous system depression, irritation of the lungs, and damage to the liver, kidney and heart. Death occurs suddenly with minimal outward signs. Dead rodents are frequently found on their belly with legs and tail spread out (Freeman et al., 1954).

Birds (including chickens) are highly sensitive to zinc phosphide, so give extra consideration to separating birds from bait sources (Christopher et al., 1982). Zinc phosphide does not accumulate in the tissues of rodents (Robertson et al., 1945), therefore the risk of secondary poisoning is greatly reduced compared to anticoagulant compounds.

Time to death

Time to death is dependent on the size of dose. Large doses have caused death in rats within 20 minutes, while low doses may take up to several days (Freeman et al., 1954; Schoof, 1970).

Evidence of resistance

There is no evidence of resistance to zinc phosphide.

APVMA-registered products containing zinc phosphide:

ZP Mouse (20 g/kg), ZP Rat (20 g/kg), Mouseoff Zinc Phosphide (25 g/kg), Rattoff Zinc Phosphide (25 g/kg), Farmalinx Zincphos (25 g/kg), Imtrade Deadmouse Zinc Phosphide (25 g/kg), Surefire Zinc Phosphide (25 g/kg), Pestmaster ZnP (25 g/kg), Last Supper (25 g/kg), 4 Farmers Zinc Phosphide (25 g/kg)

Available formulation:

- Grain bait
- Pellet bait
- Sachet bait

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	25.8-53.3 mg/kg	20 g	0.02-0.04 g*	Bell, 1972
Norway rat	27-48 mg/kg	320 g	0.3-0.6 g*	Dieke and Richter, 1946

*Calculated using a bait concentration of 25 g/kg

The table above shows the oral median lethal dose (LD_{50}) of zinc phosphide for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight of 320 grams) will eat about 20-30 grams of food daily; an adult mouse (bodyweight of 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Zinc phosphide rodenticides have a standard active concentration of 25 g/kg. Therefore, 0.3-0.6 grams of bait would be considered a lethal dose for rats and 0.02-0.04 grams of bait is lethal for mice. For both species, this is a fraction of daily food requirement. It is possible for a lethal dose to be consumed in a single feed.

Poison scheduling and regulatory requirements

Zinc phosphide is classified as a Schedule 7 Dangerous Poison. It is available only to specialised or authorised users. Regulations restricting availability, possession, storage or use may apply. Please check with your state health authority before purchasing.

Handling, storage and user safety

Store in the closed original container in a dry, cool, well-ventilated area out of direct sunlight. Do not handle near food, animal foodstuffs or drinking water. Keep out of reach of children. Do not use near heat sources, open flame or hot surfaces. As soon as possible, wash hands thoroughly after applying bait.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet.

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First-generation anticoagulant rodenticides

Anticoagulant rodenticides (ARs), originally developed for therapeutic treatment of blood clots, can counteract the neophobic behaviour of rodents because of a considerable delay between consumption of bait and the emergence of symptoms. Early commercial examples of these compounds are known as first-generation ARs. They dominated rodent control in the 1950s and 1960s. However, heavy use of these compounds led to resistant rodent strains (Rowe and Redfern, 1965; Greaves and Ayres, 1969; Hadler and Shadbolt, 1975; Thijson, 1995). First-generation ARs are still available, but their use has declined in favour of more potent compounds, known as second-generation ARs.

COUMATETRALYL

Development and use

Coumatetralyl is a first-generation hydroxycoumarin anticoagulant rodenticide that was developed in the 1950s. Along with warfarin, coumatetralyl was one of the compounds that dominated rodent control worldwide from 1950 to 1965 (Hadler and Buckle, 1992). The emergence of resistant rat and mouse strains in the UK, Europe and the USA caused a decline in coumatetralyl use, and stimulated the development of more potent second-generation anticoagulant rodenticides (Greaves and Ayres, 1969). Although it is unlikely to control warfarin-resistant strains (Rowe and Redfern, 1968), coumatetralyl is still registered in all Australian states and territories for controlling introduced rats and mice. Therefore, for effective control, users of coumatetralyl need to ensure that fresh bait is continually available.

Mode of action

Coumatetralyl exhibits the same mode of action as all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors. When the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and the onset of symptoms. Effects develop progressively, and include haemorrhage, shock, loss of consciousness, and death (Petterino and Paolo, 2001).

Metabolism of coumatetralyl occurs faster than second-generation rodenticides. The compound persists in the liver of rodents, with a half-life of 55 days for rats (Parmar et al., 1987) and 16 days for mice (Vandenbroucke et al., 2008). Coumatetralyl is excreted primarily in the faeces and, to a lesser extent, in the urine of rodents. Therefore, rat droppings and rodent carcases should be cleared from production areas as soon as possible to reduce secondary poisoning risk. Due to its relatively short metabolic half-life, coumatetralyl (along with all first-generation anticoagulant rodenticides) is more effective if administered in small daily doses rather than a large single dose (Hadler and Buckle, 1992). Therefore, effective coumatetralyl application is likely to require greater total amounts and more frequent re-application of bait.

Time to death:

- Rats: 3-17 days (Bentley and Larthe, 1959; Hagan and Radomski, 1953; Lund, 1981; Hadler and Buckle, 1992)*
- Mice: 3-21 days (Bentley and Larthe, 1959)*

*Time to death for rodents following ingestion of coumatetralyl is not explicitly reported in scientific literature. Because coumatetralyl has a shared mode of action and similar acute toxicity values, it is likely that the time to death is comparable to other first-generation anticoagulant rodenticides (namely, diphacinone and warfarin).

Evidence of resistance

Evidence of the existence of cross-resistance to all first-generation anticoagulants has been observed in Europe (Rowe and Redfern, 1965; Greaves and Ayres, 1969; Hadler and Shadbolt, 1975). To date, no resistance studies have been conducted in Australian pest rodent species.

APVMA-registered products containing coumatetralyl:

Racumin (0.37 g/kg), Racumin 8 (8 g/kg), Ratex (0.38 g.kg), Readi Rac (0.4 g/kg), Surefire Couma (0.37 g/kg)

Available formulations:

- Paste bait
- Tracking powder
- Wax block

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	>1000 mg/kg	20 g	2.5-54 g*	Vandenbroucke et al., 2008
Norway rat	16.5 mg/kg	320 g	0.66-14.3 g*	Tomlin, 2009

*Calculated using a bait concentration of 0.37-8 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of coumatetralyl for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight of 320 grams) will eat about 20-30 grams of food daily, and an adult mouse (bodyweight of 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Coumatetralyl rodenticides have a standard active concentration of 0.37-8 g/kg. Therefore, 0.66-14.3 grams of bait would be considered a lethal dose for rats and 2.5-54 grams of bait is lethal for mice. For coumatetralyl products with a higher active concentration (8 g/kg), this is within the daily feed requirements for rats and mice, and it is possible for a lethal dose to be consumed in a single feed. However, most products require repeated feeding of bait for effective control.

Poison schedule and regulatory requirements

Depending on the active concentration, coumatetralyl is either a Schedule 5 or Schedule 6 poison with a low to moderate potential for causing harm. Products containing coumatetralyl are required to have distinctive packaging with strong warnings and safety direction on the label. There are no special regulations restricting the availability, possession, storage or use of products containing coumatetralyl.

Handling, storage and user safety

Users are advised to wear gloves, safety glasses, and appropriate clothing to avoid skin and eye contact. Do not inhale dust. Do not touch the bait; use the scoop or measure. If it's on skin and after each baiting, wash thoroughly with soap and water.

Containers that have been used to house bait should not be used for any other purpose. Store in tightly sealed original containers in a dry secure place away from fertilisers, seed, feed and food. Store out of direct sunlight. Keep out of reach of children, unauthorised persons and animals.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet.

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DIPHACINONE

Development and use

Diphacinone is a first-generation indandione rodenticide developed as a more effective alternative to warfarin that had no patent restrictions (Correll et al., 1952). The emergence of rat and mouse strains in the UK, Europe and the USA with cross-resistance to all first-generation rodenticides caused a decline in diphacinone use, and stimulated the development of more potent second-generation anticoagulant rodenticides (Greaves and Ayres, 1969). Despite this, diphacinone is still registered in all Australian states and territories to control introduced rats and mice although only one product, Ramik®, is commercially available.

Mode of action

Diphacinone has the same anticoagulant mode of action shared by all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces production of blood-clotting factors, and when the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and the onset of symptoms. Effects develop progressively and include haemorrhage, shock, loss of consciousness, and eventual death (Petterino and Paolo, 2001).

Diphacinone belongs to the indandione group of anticoagulants observed to have other effects, including muscle twitching and spasms before death, when large quantities are consumed (Cahill and Crowder 1979). The compound accumulates in the liver of rodents but is metabolised quicker than other anticoagulants. It has a half-life of 3 days in rat liver (Fisher et al., 2003); in mice, 75% of the active compound is eliminated in 2-4 days (Cahill and Crowder 1979). This short metabolic half-life means that for effective control using diphacinone, repeated feeding is required (Hadler and Buckle, 1992). Therefore, users need to ensure that fresh bait is continually available. Dead or dying rodents should also be cleared from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

Rats: 3-14 days (Bentley and Larthe, 1959)

Mice: 3-21 days (Bentley and Larthe, 1959)

Evidence of resistance

Evidence of the existence of cross-resistance to all first-generation anticoagulants has been observed in Europe (Rowe and Redfern, 1965; Greaves and Ayres, 1969; Hadler and Shadbolt, 1975). To date, no resistance studies have been conducted in Australian pest rodent species.

APVMA-registered products containing diphacinone:

Ramik® (0.05 g/kg)

Available formulation:

Bait concentrate and ready-to-use nugget bait

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	141-340 mg/kg	20 g	56.4-136 g*	Correll et al., 1952; Humphreys, 1988
Norway rat	0.3-3 mg/kg	320 g	1.92-19.2 g*	Correll et al., 1952; Krieger, 2001

*Calculated using a bait concentration of 0.05 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of diphacinone for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Diphacinone rodenticides have a standard active concentration of 0.005% (0.05 g/kg). Therefore, 1.92-19.2 grams of bait would be considered a lethal dose for rats and 56.4-136 grams of bait is lethal for mice. For both species, this is greater than the daily feed requirement, therefore repeated feeding of bait is needed.

Poison schedule and regulatory requirements

Diphacinone is a Schedule 6 poison with a moderate potential for causing harm. Products containing diphacinone are required to have distinctive packaging with strong warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing diphacinone.

Handling, storage and user safety

Recommended for controlling mice in and around industrial, commercial, agricultural and domestic buildings. Do not apply bait directly to ground surface or in grass or other ground cover.

Store the material in a well-ventilated, secure area out of reach of children and domestic animals. Do not store food, beverages or tobacco products in the storage area. Prevent eating, drinking, tobacco use, and cosmetic application in areas where there is a potential for exposure to the material. Wash thoroughly with soap and water after handling.

Read the label before use. For detailed instructions on handling and user safety, please refer to the relevant Safety Data Sheet.

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WARFARIN

Development and use

Warfarin, originally developed as a therapeutic treatment for thrombosis, was identified as a potential rodenticide after exposed laboratory rodents died of haemorrhage (Mills, 1955). First controlled trials were carried out in London in 1946-47. Due to its anticoagulant mode of action and delayed onset of symptoms, warfarin performed more favourably than traditional fast-acting single-dose poisons. Warfarin was the dominant rodenticide used worldwide throughout from 1950 to 1965 (Hadler and Buckle, 1992). The emergence of resistant rat and mouse strains in the UK, Europe and the USA caused a decline in warfarin use and stimulated the development of more potent second-generation anticoagulant rodenticides (Greaves and Ayres, 1969). Although unlikely to control resistant strains, warfarin is registered in all Australian states and territories for controlling introduced rats and mice.

Mode of action

Warfarin exhibits the same mode of action as all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors. When the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and onset of symptoms. The effects of warfarin develop progressively; they include haemorrhage, shock, loss of consciousness and eventual death (Petterino and Paolo, 2001).

Warfarin accumulates in plasma and liver tissue, and is metabolised comparatively quickly compared to other anticoagulant rodenticides. A total of 90% of the compound is excreted in the urine and faeces within 14 days, while the half-life in liver tissue is 10-26 days for rats and 67 days for mice (Link et al., 1965; Barker et al., 1970; Coon and Willis, 1972; Thijssen, 1995; Fisher et al., 2003; Vandenbroucke et al., 2008). Due to this short metabolic half-life, warfarin (along with all first-generation anticoagulant rodenticides) is more effective if administered in small daily doses rather than a large single dose (Hadler and Buckle, 1992). Therefore, for effective rodent control, users of warfarin need to ensure that fresh bait is continually available. Dead or dying rodents should also be cleared from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

- Rats: 3-17 days
- Mice: 6-8 days

This is dependent on dose rate and frequency of feeding (Hagan and Radomski, 1953; Bentley and Larthe, 1959; Lund, 1981; Hadler and Buckle, 1992)

Evidence of resistance

Warfarin resistance has been observed in all three common pest rodent species (Norway rats, black rats and house mice) in the UK, the USA, throughout Europe and in Asia (Boyle, 1960; Rowe and Redfern, 1965; Greaves et al., 1976). Cross-resistance to all first-generation anticoagulants has also been observed in Europe (Rowe and Redfern, 1965; Greaves and Ayres, 1969; Hadler and Shadbolt, 1975). To date, no resistance studies have been conducted in Australian pest rodent species, but the emergence of resistant strains worldwide means it is likely to exist within Australian rodent populations.

APVMA-registered products containing warfarin:

Double Strength Ratsak (0.5 g/kg), Ratblitz (0.25 g/kg), Rat Kill (0.25 g/kg), Rat 'N' Mouse Killer (0.25 g/kg)

Available formulation:

- Paste bait
- Tracking powder
- Wax block

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	374 mg/kg	20 g	15-29.9 g*	Dubock, 1978
Norway rat	58 mg/kg	320 g	37-74 g*	Thomson, 1991

*Calculated using a bait concentration range of 0.25-0.5 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of warfarin for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Warfarin rodenticides have an active concentration of 0.25 to 0.5 g/kg. Therefore, 37-74 grams of bait would be considered a lethal dose for rats and 15-29.9 grams of bait is lethal for mice. For both pest rodent species, this is greater than their daily food requirement. Therefore, repeated feeding of bait is needed for effective control.

Poison schedule and regulatory requirements

Warfarin is a Schedule 5 poison with a low potential for causing harm. Products containing warfarin are required to have appropriate packaging with simple warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing warfarin.

Handling, storage and user safety

Avoid skin and eye contact and inhaling dust when handling baits.

Store bait in a cool, dry, well-ventilated place, out of direct sunlight and away from foodstuffs. Containers housing bait should be closed when not in use and checked regularly for spills.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet.

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Second-generation anticoagulant rodenticides

First-generation ARs dominated rodent control in the 1950s and 1960s. However, heavy use led to resistant rodent strains (Rowe and Redfern, 1965; Greaves and Ayres, 1969; Hadler and Shadbolt, 1975; Thijson, 1995), stimulating the development of second-generation of anticoagulant rodenticides (SGARs), which have a much greater potency and longer half-lives in animal tissue. SGARs are effective at controlling previously resistant strains while maintaining the delayed onset of symptoms required to prevent bait avoidance. However, because of the greater potency and persistence of these compounds in the tissues of baited rodents, they have a higher secondary poisoning risk. Livestock- and food-producing industries, in particular, need to take great care to prevent contaminating production areas from the SGAR bait itself and SGAR-baited rodents.

BRODIFACOUM

Development and use

Brodifacoum is a second-generation anticoagulant rodenticide (SGAR) that was developed in 1976 and first registered for use in the UK in 1978 (Redfern et al., 1976). While being chemically similar to first-generation anticoagulants like warfarin and coumatetralyl (all are hydroxycoumarins), brodifacoum is classified as an SGAR because it is more potent (i.e. a smaller amount of bait is needed for a kill) and effective against rodents that are resistant to earlier compounds (Hadler and Buckle, 1991). Brodifacoum is registered in all Australian states and territories for controlling introduced rat and mice species.

Mode of action

Brodifacoum exhibits the same mode of action as all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors. When the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and the onset of symptoms. The effects of brodifacoum develop progressively, and include haemorrhage, shock, loss of consciousness and eventual death (Petterino and Paolo, 2001).

Brodifacoum has a very high potency, meaning that it is possible for rodents to consume a lethal dose in a single feed as a fraction of daily food requirement (see Acute toxicity). Despite this, brodifacoum is not recommended for use as a single-application rodenticide. Field trials found that for satisfactory control, bait must be available for longer than seven days because some rodents do not feed sufficiently in a single week to acquire a lethal dose (Hadler and Buckle, 1991). Metabolism of brodifacoum occurs very slowly and the compound persists in the liver of rodents, with a half-life of 114-130 days (Fisher et al., 2003) for rats, and 307 days for mice (Vandenbroucke et al., 2008). Excretion of the compound occurs predominantly in the faeces (Laas et al., 1985). Therefore, rodent carcases should be removed from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

- Rats: 3-14 days (Lund, 1981; Saxena and Sharma, 1984; Littin et al., 2000)
- Mice: 3-18 days (Rowe and Bradfield, 1976; Lund, 1981; Newton et al., 1990)

Evidence of resistance

There is little evidence of resistance specific to brodifacoum (MacNicoll et al., 1996). Recent studies indicate that brodifacoum remains effective against warfarin-resistant rodents (Buckle et al., 2012; Meerberg et al., 2014). To date, no resistance studies have been conducted in Australian pest rodent species.

APVMA-registered products containing brodifacoum:

Brigand, Ditrac, First Formula, Mortein Mice/Rat Kill Professional, Pest Defence, Pestmaster, Protect-Us Stealth, Protect-Us Verminate, Ratal B, Raticide, Ratsak, Ratshot Red, Rodenthor, Rodex B, RoDi, Surefire, Talon, The Big Cheese, Time's Up, Tomcat II, Top Cat

NB: All products listed above have a brodifacoum concentration of 0.05 g/kg.

Available formulations:

- Grain bait
- Pelleted bait

- Paste bait
- Soft bait
- Sachet bait
- Wax block
- Extruded block

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	0.4 mg/kg	20 g	0.16 g*	Redfern et al., 1976
Norway rat	0.49 mg/kg	320 g	3.13 g*	FAO, 2015

*Calculated using a bait concentration of 0.05 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of bromadiolone for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Brodifacoum rodenticides have a standard active concentration of 0.005% (0.05 g/kg). Therefore, 3.13 grams of bait would be considered a lethal dose for rats and 0.16 grams of bait is lethal for mice. Because these volumes are within the daily food requirement of target species, it is possible for a lethal dose to be consumed in a single feed.

Poison schedule and regulatory requirements

Brodifacoum is a Schedule 6 poison with a moderate potential for causing harm. Products containing brodifacoum are required to have distinctive packaging with strong warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing brodifacoum.

Handling, storage and user safety

Wear gloves, safety glasses and appropriate clothing to avoid skin and eye contact. Do not inhale dust. Do not touch the bait. Use the scoop or measure. If on skin and after each baiting, wash thoroughly with soap and water.

Containers that have been used to house bait should not be used for any other purpose. Store in tightly sealed original containers in a dry secure place away from fertilisers, seed, feed and food. Store out of direct sunlight. Keep out of reach of children, unauthorised persons and animals.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet.

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BROMADIOLONE

Development and use

Bromadiolone is a second-generation anticoagulant rodenticide (SGAR) that was developed in France in the 1960s and introduced in 1978 (Grand, 1976). While being chemically similar to first-generation anticoagulants like warfarin and coumatetralyl (all are hydroxycoumarins), bromadiolone is classified as an SGAR because it is more potent (i.e. a smaller amount of bait is needed for a kill) and effective against rodents that are resistant to earlier compounds (Hadler and Buckle, 1991). Bromadiolone is registered in all Australian states and territories for controlling introduced rat and mice species.

Mode of action

Bromadiolone exhibits the same mode of action as all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors, and when the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and the onset of symptoms. The effects of bromadiolone develop progressively and include haemorrhage, shock, loss of consciousness and eventual death (Petterino and Paolo, 2001).

Bromadiolone is highly potent. It is possible for rodents to consume a lethal dose in a single feed as a fraction of daily food requirement (see Acute toxicity). Despite this, bromadiolone is not recommended as a single-application rodenticide. Baits should be re-applied weekly for several weeks to allow rodents to feed sufficiently to acquire a lethal dose (Hadler and Buckle, 1991). Bromadiolone undergoes minimal metabolism and is mainly excreted in the faeces of rodents. In both rats and mice, an initial phase of rapid excretion occurs for the first 4-8 days after exposure before slowing down to a rate comparative to other second-generation rodenticides (Poché, 1988). The half-life of bromadiolone is 170 days in rat liver and 28 days in mice liver (Kamil, 1987; Vandenbroucke et al., 2008). Therefore, rodent carcases should be removed from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

- Rats: 2-16 days (Meehan, 1978; Redfern and Gill, 1980)
- Mice: 3-19 days (Meehan, 1978; Redfern and Gill, 1980; Rowe et al., 1981)

Evidence of resistance

There is some evidence of cross-resistance with warfarin (Rowe et al., 1981) and difenacoum (MacNicoll et al., 1996), although not widespread (Endepols et al., 2007). Evidence exists of reduced efficacy in Norway rat species carrying specific resistance mutations in The Netherlands (Meerberg et al., 2014). To date, no resistance studies have been conducted in Australian pest rodent species.

APVMA-registered products containing bromadiolone:

Alley Cat, Bromakil, Bromakil Rat Drink (0.5 g/L), Contrac, Generation Green, Maki, MouseOff, Muskil (dual blend bromadiolone 0.025 g/kg & difenacoum 0.025 g/kg), Ratsak (dual blend bromadiolone 0.025 g/kg & difenacoum 0.025 g/kg), Rat Stop, Rentokil Bromard, Rodemise, Surefire Broma, TomCat

NB: All products listed above have a bromadiolone concentration of 0.05 g/kg unless otherwise stated.

Available formulations:

- Grain bait

- Liquid concentrate
- Pelleted bait
- Paste bait
- Soft bait
- Sachet bait
- Wax block
- Extruded block

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	0.86-1.75 mg/kg	20 g	0.4-0.8 g*	Meehan, 1978
Norway rat	0.57-0.75 mg/kg	320 g	3.6-4.8 g*	Meehan, 1978

*Calculated using a bait concentration of 0.05 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of bromadiolone for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily, and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Bromadiolone rodenticides have a standard active concentration of 0.005% (0.05 g/kg). Therefore, 3.6-4.8 grams of bait would be considered a lethal dose for rats and 0.4-0.8 grams of bait is lethal for mice. Because these volumes are within the daily food requirement of target species, it is possible for a lethal dose to be consumed in a single feed.

Poison schedule and regulatory requirements

Bromadiolone is a Schedule 6 poison with a moderate potential for causing harm. Products containing bromadiolone are required to have distinctive packaging with strong warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing bromadiolone.

Handling, storage and user safety

Wear gloves, safety glasses and appropriate clothing to avoid skin and eye contact. Do not inhale dust. Do not touch the bait; use the scoop or measure. If on skin and after each baiting, wash thoroughly with soap and water.

Containers that have been used to house bait should not be used for any other purpose. Store in tightly sealed original containers in a dry secure place away from fertilisers, seed, feed and food. Store out of direct sunlight. Keep out of reach of children, unauthorised persons and animals.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet.

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DIFENACOUM

Development and use

First registered in the UK in 1975, difenacoum was one of the earliest commercially available second-generation rodenticides (SGAR). While being chemically similar to first-generation anticoagulants (i.e. warfarin and coumatetralyl), SGARs like difenacoum are so called because they are effective against rodents that are resistant to earlier compounds, and are much more potent (i.e. smaller amounts of bait are required to be consumed for a kill). Difenacoum is registered in all Australian states and territories for controlling introduced rat and mice species.

Mode of action

Difenacoum exhibits the same mode of action as all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors, and when the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and the onset of symptoms. The effects of difenacoum develop progressively, and include haemorrhage, shock, loss of consciousness and eventual death (Petterino and Paolo, 2001).

Difenacoum is more potent than first-generation rodenticides (i.e. coumatetralyl, diphacinone and warfarin) but is the least potent second-generation compound. It is possible for mice, but unlikely that rats will consume a lethal dose in a single feed (see Acute toxicity). Therefore, difenacoum baits should be applied for several weeks to allow rodents to feed sufficiently to acquire a lethal dose (Hadler and Buckle, 1991). Difenacoum is excreted mainly through the faeces, but also through the urine of rodents. The half-life of difenacoum is 120 days in rat liver and 62 days in mice liver (Parmar et al., 1987; Vandenbroucke et al., 2008; Anon, 2009). Therefore, rodent carcases should be removed from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

- Rats: 4-13 days (Rowe and Bradfield, 1976; Rowe, 1981)
- Mice: 4-22 days (Hadler et al., 1975; Lund, 1981)

Evidence of resistance

Resistance was discovered in Norway rats specifically in Europe within a few years of commercial use (Redfern and Gill, 1978). More recently, cross-resistance has been observed with warfarin and bromadiolone (Greaves et al., 1982; Cowan et al., 1995; MacNicoll et al., 1996; Meerberg et al., 2014). There are no reports of resistance in house mice or black rats. To date, no resistance studies have been conducted in Australian pest rodent species.

APVMA-registered products containing difenacoum:

Atlas, Cougar, Effect, Muskil (dual blend bromadiolone 0.025 g/kg & difenacoum 0.025 g/kg), Patrol, PCT Pro Formula, Ratsak (dual blend bromadiolone 0.025 g/kg & difenacoum 0.025 g/kg), Ratshot, Ratshot-G, Roban, Rodemise Difenacoum, Sorexa Pro, Surefire Difenate, The Big Cheese, Time's Up, Victor

NB: The products listed above have an active difenacoum concentration of 0.05 g/kg unless otherwise specified.

Available formulation:

- Extruded bait
- Grain bait

- Liquid concentrate
- Pelleted bait
- Paste bait
- Wax block

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	0.8 mg/kg	20 g	0.32 g*	Bull, 1976
Norway rat	1.8-2.5 mg/kg	320 g	11.6-16 g*	Bull, 1976

*Calculated using a bait concentration of 0.05 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of difenacoum for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Difenacoum rodenticides have a standard active concentration of 0.005% (0.05 g/kg). Therefore, 11.6-16 grams of bait would be considered a lethal dose for rats and 0.32 grams of bait is lethal for mice. For mice, this is a fraction of daily food requirement, so it is possible for a lethal dose to be consumed in a single feed. For rats, because it is unlikely for a lethal dose to be consumed in a single feed, repeated feeding is required for effective control.

Poison schedule and regulatory requirements

Difenacoum is a Schedule 6 poison with a moderate potential for causing harm. Products containing difenacoum are required to have distinctive packaging with strong warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing difenacoum.

Handling, storage and user safety

Avoid contact with eyes and skin. Do not smoke, eat or drink while handling. Wash hands and face after handling.

Store in a cool, dry, well-ventilated area. Keep away from food and animal feedstuffs. Keep away from oxidising agents.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet for the product.

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DIFETHIALONE

Development and use

Difethialone is a second-generation rodenticide from the hydroxyl-4-benzothiopyranone chemical family that was developed in France and first used in 1986 (Lechevin, 1986). It is classified as an SGAR because it is more potent (i.e. a smaller amount of bait is required for a kill) and effective against rodents resistant to earlier compounds (Hadler and Buckle, 1991). Compared to other SGARs, difethialone is more toxic to birds and fish, and tolerated better by dogs and pigs (Lechevin and Poché, 1988). It is also incorporated into commercial baits at a lower active concentration (0.025 mg/kg instead of 0.05 mg/kg) to reduce the risk to non-target species. Difethialone is registered in all Australian states and territories for controlling introduced rat and mice species.

Mode of action

Despite being from a different chemical family to other commercially available second-generation rodenticides, difethialone exhibits the same anticoagulant mode of action (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors and eventually, when the existing supply of clotting factors are degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption of a lethal dose and the onset of symptoms. The effects of difethialone develop progressively and include haemorrhage, shock, loss of consciousness and eventual death (Petterino and Paolo, 2001).

Difethialone is highly potent. It is possible for rodents to consume a lethal dose in a single feed as a fraction of daily food requirement (see Acute toxicity). However, users are advised to re-apply bait weekly for several weeks to allow rodents to feed sufficiently to acquire a lethal dose (Hadler and Buckle, 1991). Difethialone is not metabolised well by rodents and is mainly excreted through faeces (McLeod and Saunders, 2013). Difethialone persists in rodent liver tissue with a half-life of 108 days for rats and 29 days for mice (Lechevin and Poché, 1988; Vandenbroucke et al., 2008). Therefore, rodent carcases should be removed from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

- Rats: 2-16 days (Lechevin and Poché, 1988; Nahas et al., 1989; Saxena et al., 1992)
- Mice: 2-20 days (Lechevin and Poché, 1988; Nahas et al., 1989; Saxena et al., 1992)

Evidence of resistance

There is no evidence of resistance to difethialone. To date, no resistance studies have been conducted on Australian pest rodent species.

APVMA-registered products containing difethialone:

Generation Blue (0.025 g/kg), Rodilon Pro (0.025 g/kg)

Available formulation:

- Extruded bait
- Grain bait
- Wax blocks

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	0.47-1.29 mg/kg	20 g	0.38-1.03 g*	Vandenbroucke et al., 2008
Norway rat	0.29-0.51 mg/kg	320 g	3.7-6.5 g*	Lorgue et al., unpublished (Lechevin, 1988)

*Calculated using a bait concentration of 0.025 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of difethialone for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species, and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily, and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Difethialone rodenticides have a standard active concentration of 0.0025% (0.025 g/kg). Therefore, 3.7-6.5 grams of bait would be considered a lethal dose for rats and 0.38-1.03 grams of bait is lethal for mice. Because these volumes are within the daily food requirement of target species, it is possible for a lethal dose to be consumed in a single feed.

Poison schedule and regulatory requirements

Difethialone is a Schedule 6 poison with a moderate potential for causing harm. Products containing difethialone are required to have distinctive packaging with strong warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing difethialone.

Handling, storage and user safety

Avoid contact with skin, eyes and clothing. Wash hands immediately after handling.

Store in original container. Keep containers tightly closed in a dry, cool and well-ventilated place that is accessible by authorised persons only. Keep away from direct sunlight. Keep away from food, drink and animal feedstuffs.

Read the label before use. For detailed instructions on handling and user safety, please refer the relevant Safety Data Sheet for the product.

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FLOCOUMAFEN

Development and use

Flocoumafen is a second-generation rodenticide that was first synthesised in 1984 (Bowler et al., 1984). While being chemically similar to first-generation anticoagulants like warfarin and coumatetralyl (all are hydroxycoumarins), brodifacoum is classified as an SGAR because it is more potent (i.e. a smaller amount of bait is required for a kill) and effective against rodents resistant to earlier compounds (Hadler and Buckle, 1991). Flocoumafen has been used around the world, most notably for controlling rats in rice fields in the Philippines (Hoque and Olvida, 1988). In Australia, flocoumafen is registered in all states for controlling introduced rats and mice, especially warfarin-resistant strains.

Mode of action

Flocoumafen exhibits the same mode of action as all anticoagulant rodenticides (Silverman, 1980). When a rodent eats the bait, the active anticoagulant blocks the epoxide reductase enzyme and stops the recycling of activated vitamin K. This severely reduces the production of blood-clotting factors, and when the existing supply of clotting factors are eventually degraded, the clotting mechanism fails and haemorrhaging begins. As with all anticoagulants, there is a considerable delay between consumption and the onset of symptoms. The effects of flocoumafen develop progressively and include haemorrhage, shock, loss of consciousness and eventual death (Petterino and Paolo, 2001).

Flocoumafen is highly potent. It is possible for rodents to consume a lethal dose in a single feed as a fraction of daily food requirement (see Acute toxicity). Despite this, it is not recommended for use as a single-application rodenticide. Users are advised to re-apply bait weekly for several weeks to allow rodents to feed sufficiently to acquire a lethal dose (Hadler and Buckle, 1991). Flocoumafen is not metabolised well by rodents and is mainly excreted through faeces (Huckle et al., 1988). Flocoumafen is highly persistent in rodent liver tissue, with a half-life of 220 days for rats and 94 days for mice (Huckle et al., 1988; Vandenbroucke et al., 2008). Therefore, rodent carcases should be removed from production areas as soon as possible to reduce secondary poisoning risk.

Time to death:

- Rats: 3-11 days (Rowe et al., 1985; Lund, 1988)
- Mice: 4-19 days (Bowler et al., 1984; Parshad and Chopra, 1986; Lund, 1988)

Evidence of resistance

There is little evidence of resistance to flocoumafen (Bowler et al., 1984; Rowe et al., 1985; MacNicoll et al., 1996) or reduced efficacy against warfarin-resistant strains (Meerberg et al., 2014). To date, no resistance studies have been conducted on Australian pest rodent species.

Australian-registered manufacturers/products:

Storm (0.05 g/kg), Stratagem (0.05 g/kg)

Available formulation:

- Bait concentrate
- Extruded bait
- Grain bait
- Pellet bait
- Wax block

Acute toxicity

Species	LD_{50}	Average bodyweight	Amount of bait consumed for a LD_{50}	Reference (for LD_{50})
Mouse	0.79-2.4 mg/kg	20 g	0.4-1 g*	Bowler et al., 1984
Norway rat	0.25-0.56 mg/kg	320 g	1.6-3.6 g*	Bowler et al., 1984

*Calculated using a bait concentration of 0.05 g/kg

The table above shows the oral median lethal dose (LD_{50}) values of flocoumafen for the house mouse and Norway rat, the typical bodyweight for an adult animal from each species and the total amount of commercial bait needed to be eaten to cause death. An adult rat (bodyweight 320 grams) will eat about 20-30 grams of food daily and an adult mouse (bodyweight 20 grams) will eat 2-5 grams of food daily (Hadler and Buckle, 1991). Flocoumafen rodenticides have a standard active concentration of 0.005% (0.05 g/kg). Therefore, 1.6-3.6 grams of bait would be considered a lethal dose for rats and 0.4-1 grams is lethal for mice. Because these volumes are within the daily food requirement of target species, it is possible for a lethal dose to be consumed in a single feed.

Poison schedule and regulatory requirements

Flocoumafen is a Schedule 6 poison with a moderate potential for causing harm. Products containing flocoumafen are required to have distinctive packaging with strong warnings and safety directions on the label. There are no special regulations restricting the availability, possession, storage or use of products containing flocoumafen.

Handling, storage and user safety

Segregate from foods and animal feed. Protect from temperatures above 30 °C. Protect against moisture. Protect from direct sunlight.

Do not apply baits in the open; they should be covered or placed in secure boxes. When using, do not eat, drink or smoke. Ensure ventilation of stores and work areas. Thoroughly wash hands after handling.

Read the label before use. For detailed instructions on handling and user safety, please refer to the relevant Safety Data Sheet for the product.

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Novel and emerging rodent control products

Anticoagulant rodenticides – the next generation

Anticoagulant rodenticides have long been the primary control measure in urban and rural areas. There are major problems associated with the extensive use of these compounds, namely, the risk to non-target domestic, wildlife and livestock species. This can occur by directly ingesting poisonous bait, indirectly by consuming poisoned rodents, or by consuming animal feed contaminated with faecal residues from poisoned rodents. Second-generation anticoagulant rodenticides (SGARs) are highly efficient in controlling warfarin-resistant rodents. However, there are increased concerns with high levels of reliance on these compounds and the risks associated with their use, particularly, the long-lasting persistence in the liver tissue of baited rodents (see Table 16).

Current SGARs are synthesised as a mixture of diastereomers. This means that they are essentially a mixture of compounds with the same molecular formula but with differing three-dimensional structures. Research on the toxicological properties of different diastereomers shows that while they do not differ in acute toxicity, they do differ in the rates at which they are metabolised. Therefore, the development of baits containing only the less persistent diastereomer would minimise the ecotoxicological risk associated with their use without reducing their efficacy (Damin-Pernik et al., 2016, 2017). Research on these compounds is currently in development and no compounds are produced commercially. Amidst increasing awareness of the problems associated with extensive use of anticoagulant rodenticides, future compounds have to be ethical, effective and environmentally suitable. Stronger regulations and soaring development costs have weakened commercial justification for developing new anticoagulants.

Norbormide

Norbormide (NRB) is a compound that is selectively toxic to rodents of the genus *Rattus* (including *R. norvegicus* and *R. rattus*) but relatively harmless to other animals, including other rodents (Zulian et al., 2007). It was first developed in the 1960s as a non-anticoagulant poison, and sold under the trade names Raticate and Shoxin.

NRB acts as both a vasoconstrictor and calcium channel blocker, simultaneously reducing blood flow and cardiac muscle contraction. Acute symptoms appear within 10 minutes of ingestion of a lethal dose. Rats display increased motor activity and muscle incoordination, followed by weakening of hind extremities, laboured breathing, and convulsive movements. Death occurs within 30 minutes in laboratory rats and within two hours for wild animals (Roszkowski et al., 1965). Because NRB is a rat-specific poison, it poses a lower risk of secondary poisoning of wildlife, domestic and livestock animals, which is considerable with other rodenticides.

One flaw of NRB is that it causes a rapid onset of acute effects, to the extent that rats were observed to develop an evolutionary aversion to the compound, otherwise known as bait shyness or avoidance (Greaves, 1966). Because of bait shyness and the efficacy of other types of rodenticides (anticoagulants) against a wider range of rodents, use of NRB declined significantly in the 1970s.

Landcare Research, a Crown Research Institute in New Zealand, have worked recently to develop an analogue of NRB that delays the onset of acute symptoms, theoretically preventing the development of bait shyness (Rennison et al., 2013). Extensive field and laboratory testing of this compound, named DR8 NRB, is underway in New Zealand, possibly leading to registration of the product. These tests would need to be repeated under Australian conditions before the compound is registered by the APVMA.

Non-toxic rodenticides – RatX®

RatX® is a minimum-risk pesticide formulated from non-toxic food materials. The active ingredient, corn gluten meal, acts as a dehydrating agent in rodents. Following ingestion, the corn gluten meal coats the villi of the lower intestines, disrupting receptors that prompt rodents to drink water. Dehydration commences soon after, causing blood thickening, circulatory collapse and kidney failure. Rats and mice become lethargic, lapse into a coma, and die 4-7 days after regular intake (Jokic et al., 2006).

RatX® kills rats and mice but is not harmful to other animals, including birds, livestock species, domestic animals and humans. This is due to rodents' unique digestive system, specifically to do with absorption of water in the lower gut (ConSeal International, 2012). As a non-toxic rodenticide, use of RatX® is advantageous, with less risk of secondary poisoning of wildlife, domestic and livestock animals (Importing Innovation Australia, 2017). It is also reportedly effective among anticoagulant-resistant rat and mouse populations. RatX® is registered with the APVMA as a vertebrate poison, under the trade name Ratsak Naturals®. Because it is non-toxic, it has no poison schedule or regulatory requirements for its use.

For maximal efficacy, RatX® must be the primary available food source for rodents. Therefore, producers should limit rodent access to food by securely housing grains, cleaning up feed spills and removing food waste from areas where birds are housed. Manufacturers of RatX® state that rats must consume 40-60 grams and mice must consume 10-15 grams in order to cause death. This is well beyond the daily feed intake of rats and mice, therefore repeated feeding of bait is needed for effective control, which is difficult to achieve on-farm, particularly if the local rodent population is high. Many traditional rodenticides (anticoagulants and acute poisons) provide a lethal dose from significantly smaller levels of bait intake and are therefore more likely to be effective on-farm.

Plant secondary metabolites and extracts

There is scientific interest in applying Plant Secondary Metabolite (PSM) odour mixtures to deter rodents from inflicting feed loss and damaging agricultural infrastructure (Hansen et al., 2016). If successful, PSM-based repellents could be a cost-effective and ethical alternative to poison or trapping.

There are several different classes of PSMs: plants and plant materials; essential oils and terpenoids; alkaloids and alkylamides; di-carboxylic acids, glucosinolates, phenolics and flavonoids and tannins (Hansen et al., 2016). Laboratory studies of plant materials from the common sunflower (*Helianthus annuus)*, peanut (*Arachis hypogaea*) and walnut plants (*Jugulans regia*) have observed repellent effects in Norway rats (Grant-Hoffman and Barboza, 2010). In laboratory studies, repellent effects in house mice have been observed from various essential oils, including bergamot oil, fennel oil and neem oil (Hansen et al., 2015). Studies on alkaloids from the Japanese pepper shrub (*Zanthoxylum piperitum*) found a strong post-ingestive repellent effect in Norway rats in laboratory studies (Epple et al., 2001). Research on various di-carboxylic-acids, glucosinolates, phenolics and tannins have observed repellent effects against several rodent species, although not against the commensal rodent species of concern to the Australian poultry industry (Hansen et al., 2016).

Despite extensive literature on the rodent-repellent effects of various PSMs, only a handful of products are available commercially. In Australia, two plant-based products are registered; the first is a mixture of white pepper and garlic oil; and the second is a mixture of corn mint oil, camphor oil, eucalyptus oil and methyl salicylate applied to garbage bags (APVMA PUBCRIS database, accessed June 2019). There is little published research on the repellent effects of these products, specifically against commensal rodent species.

Plant extracts have also been observed to inhibit rodent fertility by limiting a range of reproductive processes, such as gonadal function and development to gestation. Extracts from at least 40 plant species have been observed to disrupt reproductive effects at the ovarian level when orally administered to rats

and mice. Unfortunately, researchers have been unable to identify specific active compounds responsible for these reproductive effects. Furthermore, the effects of these plant extracts are short term and reversible when treatment stops (Tran and Hinds, 2013).

In summary, some plant metabolites and extracts appear to have potential to be used as humane and environmentally friendly tools for rodent management. However, inconsistent results of laboratory and field studies have ultimately led to a small number of commercially viable products that cannot be compared to the wide range of traditional rodenticide compounds.

Reproductive rodent control

Reproductive rodent control is a novel approach that aims to reduce the number of new-borne rodents recruited into the local population. Traditional control methods, such as rodenticides, focus on reducing local rodent numbers solely by increasing the mortality rate. This can reduce numbers in the short term but does nothing to prevent rodents being recruited via reproduction and migration. Long-term bait use, which is often needed to suppress numbers, can also lead to undesirable outcomes, e.g., more selection pressure for resistance, and chemical residue contamination of feed and the farm environment. Reproductive control causes a delayed response, where mortality, either naturally or via other strategies, leads to a long-lasting reduction in the rodent population (Barlow et al., 1997).

Rodents can be controlled reproductively several ways, including surgery, disease, hormones and chemicals. Surgery (e.g. castration, ovariectomy, vasectomy and tubal ligation) is useful because its effects are permanent, but impractical for high-density field populations. *Capillaria hepatica,* a species of threadworm that is a natural rodent parasite, has potential to disrupt rodent reproduction (Spratt and Singleton, 1986). Field tests found it to be ineffective, particularly in low populations, because widespread parasite transmission could not be achieved (Singleton and Spratt, 1986). Risks that the parasite could be transmitted to rodent predators and, potentially to humans, make it unsuitable for rodent control.

ContraPest is a liquid contraceptive product designed as a bait additive to reduce the reproductive capacity of black (*R. rattus*) and brown rats (*R. norvegicus*). When ingested, the active compounds, Vinylcyclohexene dioxide and triptolide, inhibit sperm production (Hikim et al., 2000; Huynh et al., 2000) and cause the breakdown of ovarian follicles (Mayer et al., 2002, 2004; Xu and Zhao, 2010). ContraPest functions as a contraceptive – not a sterilant – therefore ongoing consumption is required for long-term effect. Trials on laboratory rat strains and wild-caught brown rats in the USA have demonstrated that the product is effective in suppressing reproductive capability. However, the duration of effects in wild rats in the field is also not known and there are no definitive studies demonstrating long-term effects using well-designed and replicated field trials (Brown and Henry, 2018). Despite this, ContraPest was registered and approved for commercial use in the USA by the Environmental Protection Agency (EPA) in August 2016. Although it is not APVMA-registered in Australia, this product has the potential to be applied in poultry operations.

Levonorgestrel and quinestrol are contraceptive hormones that are potential candidates for reproductive rodent control. They have been shown to impair rodent reproductive performance by reducing the size and function of male reproductive organs, disrupting sperm production, concentration and motility, and reducing female reproductive rate and litter size by inducing uterine oedema (Zhang, 2015). These hormones have been trialled in a 2:1 formula, known as EP-1, in attempts to control Mongolian gerbil (*Meriones unguiculatus*) populations in northern China. EP-1 was found to delay normal reproductive patterns, suppress birth rates, reduce the density and alter the age structure of the gerbil population (Fu et al., 2013). Laboratory trials have also shown levonorgestrel and quinestrol cause long-term anti-fertility effects in several rodent species (Brandt's vole, Mongolian gerbils, and plateau pikas) (Zhang, 2015; Massawe et al., 2018). There are concerns about potential environmental contamination; however, both have relatively short half-lives (5-16 days) under field conditions, minimising the risk of non-target effects (Massawe et al., 2018). Levonorgestrel and quinestrol are promising candidates for reproductive rodent control, but more field testing is needed, specifically of Australian rodent species.

Other chemicals act as either agonists (facilitators) or antagonists (blockers) of gonadotrophin-releasing hormone (GnRH), which can cause male and female rodents to be infertile (Becker and Katz, 1997). Critically, hormonal effects are not permanent and may reach only a small proportion of the target population. Synthetic steroids, anti-steroids and anti-steroid receptors (e.g. diethylstilbestrol, RU486) can inhibit reproduction in rodents. Prolactin inhibitors can be used to disrupt lactation and gestation (e.g. bromocriptine, cabergoline) (Jochle, 1997). These chemicals are cost effective, widely available and can be delivered orally via baits or incorporated into implants. However, they must be regularly administered to ensure effectiveness and they can potentially affect non-target species.

The greatest barrier to controlling rodent fertility in the field is the widespread delivery of reproductive inhibitors to local and migrant populations (Chambers et al., 1999). Without this, there is no way to prevent fertile rodents from migrating onto farms and undermining successful reduction in local rodent population growth. More research is needed to develop species-specific mechanisms to effectively deliver anti-reproductive agents (Brown and Henry, 2018). Reproductive rodent control is a potentially useful strategy in poultry operations.

Biological rodent control

Cats are historical predators of small rodents, particularly mice. When introduced on-farm, they instinctively stalk, hunt and kill a small number of rodents. The on-farm presence of cats can influence rodent behaviour, with the higher predation risk making them less likely to move from shelter (Themb'alilahlwa et al., 2017). Cats can also prey on birds, with young chicks particularly vulnerable, so they should be denied access to areas where birds are contained. This has the flow-on effect of making sheds and poultry houses safe spaces for rodents, potentially increasing rodent populations in internal production areas, and raising disease and contamination risk. Cats also serve as intermediate hosts for the intracellular parasite *Toxoplasma gondii*, which is shed in cat faeces. It can infect all warm-blooded animals, posing a risk to the health of chickens and humans (Meerberg et al., 2014).

The use of anticoagulant rodenticides, which persist in the liver tissue of baited rodents, can lead to the secondary poisoning of cats that predate them (Gillies and Pierce, 1999). Therefore, using cats to supplement chemical control strategies is not viable. Cats can suppress rodent activity, but are unlikely to significantly reduce on-farm rodent numbers (Mahlaba et al., 2017; Brown and Henry, 2018). Because cats also pose a potential hazard to bird and human health, they are not recommended as a suitable rodent control method in poultry operations.

Domestic dogs are commonly used on farms and homes around the world to control rodents, although there is a lack of practical scientific evidence about their level of impact on rodent activity and abundance. Similar to cats, dogs may hunt and kill small numbers of rodents, but because rodents reproduce rapidly, dogs are unlikely to significantly reduce rodent populations on-farm. The presence of dogs on-farm has been observed to create a heightened fear for foraging rodents (Themb'alilahlwa et al., 2017). As a result, rodents become less likely to move from shelter or cover, and overall rodent activity is reduced.

Domestic dogs can serve as well-rounded biological control agents, suppressing rodent activity and acting as deterrents for foxes and wild dogs that pose a threat to livestock. However, as with all biological rodent control agents, the use of chemical rodenticides, either anticoagulants or acute poisons, exposes them to secondary poisoning. While dogs will not typically feed on rodents, they are susceptible to anticoagulant rodenticides. Numerous examples of anticoagulant toxicoses from the inadvertent consumption of bait are published in veterinary literature (Sheafor and Couto, 1999; Valchev et al., 2008; Waddell et al., 2013; DeClementi and Sobczak, 2018). The use of dogs to supplement existing chemical rodent control strategies is potentially hazardous. Poultry producers who use rodenticide baits alongside domestic dogs must ensure that bait is securely housed in lockable, tamper-proof bait stations.

Rodents are a natural part of the diet of Australian native birds, including the barn owl (*Tyto alba*), Australian boobook (*Ninox boobook*) and laughing kookaburra (*Dacelo novaeguineae)*. Therefore, native prey bird species are potential candidates for biological rodent control on poultry farms. In many parts of the world, barn owls are used to control rodents (Charter et al. 2010; Meyrom et al., 2009; Motro et al., 2010; Taylor, 1994). They feed on all rodent species found on poultry farms and can be attracted or introduced to specific sites by providing hollow nesting boxes (Newton, 1998). Unfortunately, most other native bird species have natural habitats that can span hundreds of hectares, therefore there are practical limitations in attracting and containing them within the areas near poultry operations.

Using native bird species alongside chemical rodent control may lead to secondary poisoning. Scientific evidence implicates current wide use of anticoagulant rodenticides as the source of some wildlife poisoning (Mendenhall and Pank, 1980; Martin et al., 1994; Thomas et al., 2011; Murray, 2018). Wild bird species are also potentially implicated with the spread of poultry diseases, including Newcastle disease virus and avian influenza (Ip et al., 2015; Brown and Bevins, 2017). The use of native predatory birds to control rodents on Australian poultry operations is novel, but due to the potential environmental and biosecurity implications, it is not recommended.

Electronic rodent control measures

Electronic rodent repellents are advertised as safe, ethical and environmentally friendly alternatives to traditional control measures, such as baits and traps. Commercialised devices typically use one of three mechanisms (electromagnetic, ultrasonic, or ionic emissions) to repel rodents and other common pests. Electromagnetic devices use electric and magnetic fields to create vibrations (electromagnetic waves) at varying rates (frequencies) designed to disrupt and repel rodent invaders. Electromagnetic waves are reportedly picked up as vibrations by rodents, disrupting their attempts to forage for food, build nests and communicate with one another. However, there is a lack of scientific evidence showing that devices of this type are measurably effective at fulfilling these claims (Howard and Marsh, 1985). Therefore, electromagnetic rodent control devices should be viewed with considerable scepticism by regulators and consumers (Bomford and O'Brien, 1990).

Ultrasonic devices emit high-pressure sound waves at frequencies beyond the limit of human hearing but audible to pests such as rats and mice. High-intensity ultrasonic sound has been shown to elicit flight responses in rats; these devices were once heralded as promising rat repellents (Pinel, 1972 & 1974). However, multiple published studies discredit the practical application of ultrasound as a viable rodent control method (Shumake et al., 1982; Howard and Marsh, 1985; Monro and Meehan, 1987). Any observations of efficacy are generally short-lived because rodents quickly adjust to the sound in a process called habituation (Bomford and O'Brien, 1990; Clapperton, 2006) or learn to avoid the source of the offending noise stimulus altogether. Furthermore, there are issues with the practical application of these devices. Ultrasonic waves cannot pass through solid objects or turn around corners, and commercial units have a short active range. Use of these devices is best suited to corridors and unobstructed areas that allow sound waves to be propagated freely. Therefore, many devices would be needed to cover an entire poultry operation, which limits the viability of agricultural application of this technology.

Ionic devices emit negatively charged atoms, similar to those produced naturally in the atmosphere before a lightning storm. Animals, which are naturally sensitive to these negatively charged ions, supposedly become confused and frightened and, as a result, seek shelter beyond the range of these devices. While there is limited peer-reviewed research demonstrating that these devices reduce the burden of rodents, ionisation has been shown to reduce airborne transmission of dust, ammonia and pathogenic bacteria, such as *Salmonella,* in poultry operations (Holt et al., 1999; Mitchell et al., 2002; Mitchell et al., 2004). It should be noted that this research involved the use of large-scale electrostatic space charge systems (ESCS) rather than the small commercial ionising units marketed specifically for rodent control.

Other rodent control measures include the electronic monitoring of rodent activity. Devices are typically small battery-powered units that use motion and temperature sensors to identify the presence of rodents. The ability to accurately monitor on-farm rodent activity enables producers to identify hotspots and to implement targeted control, improving outcomes and minimising damage. This technology could also be used to assess the efficacy of current control strategies by observing changes in rodent activity. However, because of their limited detection range, it might not be practical to use these devices to assess rodent activity throughout an entire poultry operation. To counteract this, producers are recommended to use data from a range of measures to assess the effectiveness of rodent control strategies. These might include electronically tracked rodent activity as well as visual observations of rodents, bait intake, and other signs of activity (e.g. droppings, nests, structural damage).

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Appendix

Poison schedule classifications:

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.

Glossary

APVMA: Australian Pesticides and Veterinary Medicines Authority

AR: Anticoagulant rodenticides – compound that blocks the vitamin K cycle, resulting in the inability to produce essential blood-clotting factors

Half-life: The period of time required for the concentration or amount of drug to be reduced by one half

LD_{50} (lethal dose 50% or median lethal dose): The dose of a compound required to kill half of the members of a tested population over a specified time frame. Oral LD_{50} is measured in mg of toxin per kg of bodyweight of the animal.

Neophobic: The behavioural tendency to dislike new or novel things

Neophilic: The behavioural tendency to explore or investigate new or novel things

NRB: Abbreviated term for norbormide

PSM: Abbreviated term for plant secondary metabolites – specialised compounds produced by plants that do not aid in growth and development but are required for plant survival

SGAR: Second-generation anticoagulant rodenticide – class of ARs with greater potency and a longer half-life than first-generation ARs, enabling these compounds to be effective against resistant rodent strains

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