PESTICIDES (MAMMAL)

DESLEY A. WHISSON
Deakin University, Melbourne, Victoria, Australia

A "pesticide" is defined here as any toxic material that kills a pest. For mammals, this includes materials that are inhaled (i.e., fumigants) or consumed (i.e., toxic baits). These materials are often referred to as "vertebrate pesticides," a category that also includes materials used to control birds, reptiles, fish, and amphibians; "rodenticides" (for rodents); or "predacides" (for predators). Pesticides have been used in the management or eradication of a diversity of invasive mammals including rodents, possums, rabbits, cats, canids such as the European red fox (*Vulpes vulpes*), mustelids (ferrets and stoats in New Zealand), and feral pigs (*Sus scrofa*). Vertebrate pesticides have a long history of use in urban and agricultural situations; however, they are increasingly being used in natural environments (especially islands) to mitigate impacts of invasive species. In most countries, vertebrate pesticides must be approved for sale and use by a government agency. Regulatory toxicology studies are usually conducted before a vertebrate pesticide is registered for use and are used proactively to assess the risk of the compound to humans, pets, livestock, wildlife, and the environment. They may also be conducted on older products to provide additional toxicology data required to meet new registration standards.

BURROW FUMIGANTS

Burrow fumigants include carbon monoxide, aluminium phosphide, hydrogen cyanide, carbon disulfide, methyl bromide, acrolein, and chloropicrin. Many of these are no longer used due to animal welfare concerns. Depending on the fumigant and target species, gases may be allowed to disperse passively or are mechanically propelled throughout burrows, warrens, or dens. Because burrow fumigation is labor intensive and costly, it is generally used only as a follow-up to other methods.

TOXIC BAITS

Toxic baits generally fall into two categories: anticoagulants (compounds that inhibit the synthesis of vitamin K – dependent clotting factors in the liver) and nonanticoagulants (all other toxicants).

Anticoagulant pesticides have predominantly been used for commensal rodent control but have also played a major role in the eradication and management of rodents in natural environments. Anticoagulants are also used for the management of common brushtail possums (*Trichosurus vulpecula*) in New Zealand. Anticoagulants were developed as pesticides in the 1940s following their use in human medicine. They are chemically separated into two general groups: the hydroxycoumarins (e.g., warfarin) and the indandiones (e.g., diphacinone), and they act by inhibiting synthesis of vitamin K – dependent blood-clotting factors in the liver. Animals poisoned with anticoagulants typically die within 3 to 10 days from internal haemorrhaging as a result of a loss of the blood's

From Daniel Simberloff and Marcel Rejmánek, editors, *Encyclopedia of Biological Invasions*,
Berkeley and Los Angeles: University of California Press, 2011.

clotting ability and increased permeability of capillaries throughout the body. The lengthened clotting time (prothrombin time, or PT) from a toxic dose of anticoagulant may be evident within 24 hours but usually reaches a maximum in 36 – 72 hours. Prior to death, the animal may exhibit increasing weakness due to blood loss. Because of the slow action of anticoagulants (due to the long half-life of blood-clotting factors), the target animal does not associate poisoning symptoms with the bait eaten and does not become "bait shy." This is an advantage when one is dealing with neophobic species that may hesitate to feed on a novel food. The animal can accumulate a lethal dose after multiple small feeds on the bait. The slow action of anticoagulants also has a safety advantage because it provides time to administer the antidote (vitamin K_1) to nontargets (humans, pets, other wildlife) that may have ingested bait. A disadvantage of anticoagulants is that toxic residues accumulate in tissues and in the liver of the animal consuming the bait. This presents a risk to predators and scavengers that may feed on a poisoned animal (i.e., secondary poisoning).

Warfarin was the first anticoagulant pesticide developed and is one of a group of compounds known as "first-generation" anticoagulants. Other first-generation anticoagulants include pindone, diphacinone, chlorophacinone, and coumatetralyl. With these anticoagulants, animals must consume multiple doses of the bait over a period of up to two weeks to elicit a toxic effect. The development of resistance to first-generation anticoagulants in commensal rodent populations has been a major issue affecting use of these compounds. Resistance of rats to warfarin was first observed in Scotland in 1958 following several years of continued use of this compound. Soon afterward, anticoagulant resistance was identified in both rats and house mice in other European countries, and later in the United States. Rats and mice that are resistant to warfarin are cross-resistant to all first-generation anticoagulants. Warfarin resistance stimulated developmental research on new rodenticides (both anticoagulant and nonanticoagulant) and resulted in the "second-generation" anticoagulants bromadiolone, brodifacoum, difenacoum, flocoumafen, and difethialone.

Second-generation anticoagulants have higher toxicity (lower LD_{50}), and longer persistence than the first-generation anticoagulants, and they require only a single feed of sufficient bait to elicit a toxic response. The effects of these compounds are also cumulative. As with the first-generation anticoagulants, death is delayed for several days following ingestion of a lethal dose. The greater persistence and toxicity of second-generation anticoagulants also increases the risk of poisoning of nontarget animals. Residues can remain in body tissues for long periods (months), because they are not readily metabolized. Secondary poisoning with anticoagulants has been well documented in a wide range of native birds and mammals. Resistance to second-generation anticoagulants has been observed, primarily in European countries.

For control of invasive mammals in natural environments, diphacinone and brodifacoum have had the most widespread use. Brodifacoum (3-[3-(40-bromo-[1,10-biphenyl]-4-yl)-1,2,3,4-tetrahydro-1-naphthalenyl]-4-hydroxy-2H-1-benzopyran-2-one), a second-generation anticoagulant, has been successfully used to eradicate invasive rats (*Rattus rattus*, *R. exulans*, *R. norvegicus*) on many islands worldwide. The greater persistence and potency of brodifacoum makes it ideal for use in rat eradications. Although there is a high risk of nontarget poisoning associated with this compound, the risks are generally considered to be short term and to be outweighed by the long-term benefits of rat removal. Rapid recovery of native species' populations following invasive rat eradication with brodifacoum is commonly reported. Brodifacoum has also been used in New Zealand for control of common brushtail possums.

When invasive rodents must be managed in areas where the risk of nontarget poisoning is unacceptably high, less persistent or less toxic anticoagulants are often used. Diphacinone (2-(diphenylacetyl)-1,3-indandione), a first-generation anticoagulant, has been successfully used to eradicate rats from islands including Buck Island (Virgin Islands of the United States) and the South Island of the San Jorge Islands (Mexico). Diphacinone also has been used for controlling invasive rat populations in forests in Hawaii and Puerto Rico.

Nonanticoagulant pesticides (organic and inorganic compounds) include strychnine, sodium cyanide, zinc phosphide, sodium monofluoroacetate (1080), cholecalciferol, calciferol, bromethalin, alpha-chlorohydrin, arsenic, red squill, flupropadine, and para-aminopropiophenone. They have different modes of action that may be either acute (i.e., with a single feed required) or chronic (i.e., with multiple feeds required). Many of the older pesticides, formally referred to as the acute toxicants (e.g., arsenic and red squill), either are no longer registered or are rarely used due to their ineffectiveness or high risk relative to newer pesticides. Ineffectiveness of nonanticoagulants has often been attributed to the rapid

onset of poisoning symptoms resulting in bait shyness. Newer nonanticoagulant pesticides (e.g., cholecalciferol and bromethalin) have a slower action so that bait shyness rarely occurs.

Nonanticoagulants are commonly used for commensal rodent control, although some (e.g., zinc phosphide, cyanide, cholecalciferol, and sodium monofluoroacetate) are used in field baiting programs. Of these, 1080 (sodium monofluoroacetate) has had the most widespread use and application for control of a diversity of invasive mammals. It is well known as a predacide but has also been used to manage common brushtail possums in New Zealand, feral pigs (*Sus scrofa*) in Australia, and European rabbits (*Oryctolagus cuniculus*). Its use in some countries has been discontinued due to concerns over its risk to nontarget species, persistence in the environment, and humaneness. A naturally occurring secondary plant compound, 1080 has evolved at high concentrations in some plant species as a defense mechanism against browsing invertebrates and vertebrates. Once ingested, monofluoracetate is converted within the animal to fluorocitrate, which inhibits the tricarboxylic acid cycle. This results in an accumulation of citrate in tissues and plasma, energy deprivation, and death as a result of cardiac or respiratory failure. Clinical signs of 1080 poisoning in mammals occur between 0.5 and 3 hours following ingestion and may include drowsiness, tremors, convulsions, nausea, and vomiting. Although 1080 is rapidly eliminated from living animals, it can persist in carcasses for periods of up to several months and therefore generate high secondary poisoning risks.

Sensitivity of mammals to 1080 varies widely. Dogs are extremely susceptible, and most other carnivores are highly sensitive. In some areas, native animals that forage in areas where fluoracetate-producing plants (e.g., plants of the genus *Gastrolobium*) are common have evolved a tolerance to the pesticide. This tolerance therefore reduces the nontarget hazards of baiting with 1080. In Western Australia where this occurs, 1080 has been an important component of a program known as "Western Shield," which was initiated in 1996 and aims to recover native fauna that have been adversely impacted by invasive predators (foxes and cats). The program, has involved aerial application of 1080 baits to around 3.5 million hectares of land several times each year.

Controversy over the use of 1080 has led to research into other predacides. Para-aminopropiophenone (PAPP) has been identified as an effective predacide that may be more target specific and humane than 1080. PAPP induces methaemoglobinaemia, which prevents oxygen from binding to red blood cells. This reduces the oxygen supply to the brain, and animals become lethargic and then unconscious prior to death in one to two hours.

BAITING STRATEGIES

Choice of a pesticide and how it is applied is influenced by many factors, including the target species, pesticide type and efficacy, desired outcome (i.e., eradication or control), location, potential environmental and nontarget hazards, resources available, regulations, and socio-political issues. As with other control methods, timing and the area treated are important considerations in developing an effective program using pesticides.

Vertebrate pesticides may be applied to a variety of baits including grains, vegetables, meats (fresh or dried), offal, and eggs, and there are commercially manufactured baits such as pellets, blocks, pastes, and gels that aim to improve target specificity. Mold inhibitors, attractants (olfactory or visual lures), insect repellents, and dyes may be added to improve the attractiveness, target specificity, or shelf life of baits. Concerns over the humaneness of some vertebrate pesticides have prompted research into the addition of analgesics into baits to reduce possible pain and distress associated with poisoning symptoms.

Bait application rates vary depending on the target species (population density, home range size, and habitat use) as well as the pesticide and the method of bait presentation. Bait must be applied at a rate that allows each target animal to obtain a lethal dose while minimizing the risk of excessive bait being available to nontargets. The pattern of bait placement is also an important consideration, as this can affect the frequency with which baits are encountered by both target and nontarget animals. In predator control programs, placement of baits along roads or tracks can increase the bait encounter rate of dogs and foxes that use these paths.

Bait may be applied in bait stations or other delivery devices, or by hand or aerial broadcasting. Bait may also be buried (e.g., for control of European red foxes in Australia) to reduce the potential for nontarget poisoning. In many cases, multiple delivery methods are used. Bait stations are commonly used to deliver multiple-feed anticoagulant pesticides. They can be designed to be accessible only to the target species, so they are often useful in areas where the risk of nontarget poisoning is high. The spacing of bait stations must consider the home range and habitat use by the target species so that all target animals have access to the bait. The

M-44 ejector is a bait-delivery device used to deliver predacides. This mechanical device delivers a dose of toxicant (in powder form) into the mouth of an animal biting the trigger mechanism (Fig. 1). Activation of the ejector requires significant upward force such that only relatively large animals are likely to be capable of releasing the trigger. Because the ejector is anchored in position, the risk of bait caching (common with some predators) is eliminated. Sodium cyanide is commonly used in these units. The powder reacts with the moisture in the animal's mouth, releasing hydrogen cyanide gas. Death occurs from ten seconds to two minutes after the device is triggered (Fig. 2).

In addition to minimizing bait exposure to nontarget species, bait stations allow bait uptake to be monitored and can be used in combination with nontoxic baits or tracking boards or pads to monitor the effectiveness of a control program. However, the approach is labor intensive and potentially expensive at large scales and may be impractical in rugged terrain with inaccessible areas. Regular visits to monitor bait stations can also result in disturbance of sensitive species (e.g., breeding seabirds).

Aerial broadcast is a common delivery method for vertebrate pesticides and is often used where concerns about nontarget poisoning are low. It is more cost-effective than bait stations, and bait can be applied to large or inaccessible areas. Broadcasting bait also increases the potential for all individuals in the population to access bait. It has been used as the primary method of delivering poison bait in rodent eradication programs on islands, for predator control (e.g., fox control in Western Australia), and for possum control in New Zealand.

FIGURE 1 A set M-44 ejector. When the target animal pulls on the baited ejector head, a spring-loaded plunger propels through a capsule containing the toxicant (center of the head), discharging the contents into the animal's mouth. (Photograph courtesy of Rob Hunt, NSW DECCW.)

FIGURE 2 A discharged M-44 ejector (foreground) with the carcass of the targeted fox nearby. (Photograph courtesy of Rob Hunt, NSW DECCW.)

SEE ALSO THE FOLLOWING ARTICLES

Eradication / Islands / Mammals, Aquatic / Rats / Rodents

FURTHER READING

Brakes, C. R., and R. H. Smith. 2005. Exposure of non-target small mammals to rodenticides: Short-term effects, recovery and implications for secondary poisoning. *Journal of Applied Ecology* 42: 118 – 128.

Donlan, C. J., G. R. Howald, B. R. Tershy, and D. A. Croll. 2003. Evaluating alternative rodenticides for island conservation: Roof rat eradication from the San Jorge Islands, Mexico. *Biological Conservation* 114: 29 – 34.

Greaves, J. H., A. P. Buckle, and R. H. Smith, eds. 1994. *Rodent Pests and Their Control*. Wallingford: CAB International.

Howald, G., C. J. Donlan, J. P. Galvan, J. C. Russell, J. Parkes, A. Samaniego, Y. Wang, D. Veitch, P. Genovesi, M. Pascal, A. Saunders, and B. Tershy. 2007. Invasive rodent eradication on islands. *Conservation Biology* 21: 1258 – 1268.

Hyngstrom, S. E., R. M. Timm, and G. E. Larson, eds. 1994. Prevention and Control of Wildlife Damage. Nebraska Cooperative Extension Service, University of Nebraska, Lincoln, USDA-APHIS-Animal Damage Control, and Great Plains Agricultural Council.

Marsh, R. E. 2001. Vertebrate pest control chemicals and their use in urban and rural environments (251 – 262). In R. I. Krieger, ed. *Handbook of Pesticide Toxicology: Principles and Agents*, 2nd ed. San Diego, CA: Academic Press.

Nelson, J. T., B. L. Woodworth, S. G. Fancy, G. D. Lindsey, and E. J. Tweed. 2002. Effectiveness of rodent control and monitoring techniques for a montane rainforest. *Wildlife Society Bulletin* 30: 82 – 92.