REVIEW ARTICLE

Repellents with potential to protect kea and other native birds from aerial poisoning for possum and rat control

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Abstract: Concern about non-target risks to native birds, particularly kea (*Nestor notabilis*), from aerial poisoning has prompted the evaluation of potential repellent compounds that could be incorporated into the cereal pellet bait used for possum (*Trichosurus vulpecula*) and rat (*Rattus* spp.) control. Initial trials of d-pulegone and anthraquinone were not wholly successful, with the former having poor stability in bait and the latter reducing bait uptake by rats. While research to stabilise d-pulegone in bait remains an option, a review of alternative compounds was undertaken to assist with decision-making about future directions for research, including consideration of possible formulation issues and cost. Most of the information reviewed related to use of repellents for crop protection where the aim is to reduce economic loss rather than prevent feeding on the crop, whereas preventing feeding is the primary aim for native bird protection. A further constraint was the lack of information for many compounds on response of rodents and possums. Cinnamamide, tannic acid, caffeine, garlic oil, ortho-aminoacetophenone, and thiram were identified as possible candidates and evaluated in relation to their potential to repel native birds from eating cereal baits without affecting efficacy for possums and rats. Cinnamamide, caffeine, and thiram, while effective as bird repellents, are likely to be repellent to rats at concentrations suitable for use with native birds, including kea. The little information found suggested that garlic oil was repellent to birds; it has not been formally tested on possums and rats, but anecdotal evidence did not suggest strong aversion. Ortho-aminoacetophenone appears effective as a bird repellent, but its repellency for possums and rats requires clarification. Tannic acid has some efficacy as a bird repellent, and is not repellent to possums and rats at lower concentrations. It is not clear if tannic acid exerts its effect solely as a primary repellent or whether it also has secondary repellent effects. In order from most to least promising, tannic acid, ortho-aminoacetophenone, and garlic oil are worthy of further investigation. Because each compound has demonstrated some efficacy as a bird repellent, initial testing should focus on screening against possums and rats.

Keywords: anthraquinone; cinnamamide; d-pulegone; garlic oil; kea; non-target risk; ortho-aminoacetophenone; tannic acid; thiram

Introduction

In New Zealand, management agencies conduct widespread control of introduced mammals, particularly brushtail possums (*Trichosurus vulpecula*) and rodents (*Rattus* spp.) because of their impacts on native biodiversity and agricultural production (King 2005). Among the control methods used, aerial poisoning is used primarily for extensive control (Fisher et al. 2011). Improvements in best practice for aerial poisoning over the last 20 years (Nugent et al. 2011, 2012) have significantly reduced the risks to non-target species, particularly native birds (Spurr 2000; Veltman & Westbrooke 2011). However, a risk assessment in 2011 of aerially applied cereal bait containing the toxin 1080 (sodium fluoroacetate) identified an unacceptable risk of exposure for kea (*Nestor notabilis*), an endemic New Zealand mountain parrot (Crowell et al. 2015a). Subsequently, the Department of Conservation began a research project with TBfree New Zealand, Landcare Research, and the Kea Conservation Trust to develop, register and implement an effective bird repellent to minimise kea deaths. Such a product, if successful, would likely also provide protection to a wider range of native bird species. This would be advantageous not just for non-target protection during aerial poisoning but also to protect native birds that might access toxic baits in bait stations used for ground control.

Criteria for an effective bird repellent were defined for the project as (1) wild kea consume very little (if any) repellent-treated toxic bait; (2) possum and rat kills continue to be high when repellent is used; (3) the welfare impact on poisoned possums and rats is not increased by the addition of repellent; (4) repellents are effective for 4 to 12 weeks after bait manufacture to allow for storage of baits prior to aerial operations; and (5) the additional cost of repellent is affordable. This review mostly addresses information on repellent compounds with potential to satisfy criteria 1, 2, 4, and 5.

Repellents are usually classed as primary repellents, which act through unpleasant taste or smell or irritant properties, or secondary repellents, which cause an unpleasant physiological response soon after ingestion and learned avoidance involving sensory cues provided by the formulated bait (Clark 1998). The initial focus on repellents to reduce the risk of poisoning of kea was on d-pulegone as a primary repellent and anthraquinone as a secondary repellent (Orr-Walker et al. 2012; Cowan et al. 2015), a strategy shown to be effective for crop protection and for deterring North Island robins (*Petroica longipes*) and tomtits (*P. macrocephala*) from pecking at pest control baits (Day et al. 2003; Clapperton et al. 2011, 2014; Day et al. 2012). However, laboratory and field trials demonstrated that anthraquinone reduced cereal bait consumption by rats at concentrations of 0.1% and 0.25% and hence the efficacy of 1080 cereal pellets for rat control (Cowan et al. 2015; Crowell et al. 2015b). However, Clapperton et al. (2015) concluded from trials using slices of carrot surface-coated with repellent that anthraquinone at concentrations of 0.04% or 0.08% was possibly acceptable to rats. These lower concentrations of anthraquinone as a surface coating were sufficient to reduce feeding by robins and tomtits (Clapperton et al. 2014), but their efficacy for repelling kea is unknown.

The volatility of d-pulegone was a problem because much of it was lost during bait manufacture and further loss occurred during storage (Crowell et al. 2015a). Also, some doubts were raised about its efficacy as a primary repellent for kea when 14.7% of monitored kea died from consuming 1080 cereal baits containing d-pulegone in an aerial 1080 operation (van Klink & Crowell 2015). These results led to alternative repellents being reviewed to widen the range of repellent options under consideration. In addition to repellent efficacy, an initial assessment was made of likely stability during the bait manufacturing process and the potential increase in cost of bait.

Most of the information reviewed related to use of repellents for crop protection where the aim was to reduce economic loss by reducing feeding on the crop to an economically acceptable level, whereas preventing feeding to minimise risk of toxin intake is the primary aim for native bird protection in animal pest control. A further constraint for many compounds was the lack of or conflicting information on response of rodents and possums. A previous review (Spurr 2008) provided a starting point for identifying candidate options. Methyl anthranilate and dimethyl anthranilate were dismissed because they repelled Norway rats over the concentration range likely to be effective against kea (Spurr et al. 1995, 2001) and because the formulated compound degraded quickly when used as a spray (Clark 1998; Werner et al. 2005) or required encapsulation (Cummings et al. 1995), suggesting possible formulation issues. Methiocarb is an effective bird repellent for crop protection but was discounted because its effects are dose-dependent and some deaths of birds have been recorded during its use (Porter 1977; Dolbeer et al. 1994) so the risk to kea was considered too high (J Reardon, pers. comm.). Aluminium ammonium sulphate, a highly astringent compound, is marketed as a bird repellent (e.g. Curb), but is also known to be highly repellent to small mammals (Stone 1979; Willoughby et al. 2011) so was not considered further. Neem (*Azadirachta indica*) oil was discounted as it did not repel sparrows from treated food (Day et al. 2012) but it did repel rodents, including ship rats (*R. rattus*) (Singla & Parshad 2007). Other essential oils, citronella and eucalyptus, also repelled ship rats and so were not considered further (Singla & Kaur 2014; Singla et al. 2014). Cinnamamide, tannic acid, caffeine, garlic oil, ortho-aminoacetophenone, and thiram were identified as potential candidates, partly on the basis of Spurr's (2008) review of existing literature on repellency of compounds for birds, possum and rats, and recommendations. These were evaluated in relation to their potential to repel native birds from eating cereal baits for possum and rat control without affecting efficacy for possum and rats.

Cinnamamide

Cinnamamide is a synthetic derivative of the plant secondary compound cinnamic acid. Cinnamic acid and many of its derivatives have been evaluated as potential bird repellents (e.g. Crocker et al. 1993a; Watkins et al 1999), but cinnamamide is the most well characterised and was considered the most effective repellent (Watkins et al. 1995, 1999; Gill et al. 1998b). It is unclear whether it is principally a primary or secondary repellent as its repellent effect appears to be dose dependent (Watkins et al. 1995), avoidance may not occur immediately, and it is capable of inducing experimental conditioned avoidance (chestnut-capped blackbirds (*Agelaius ruficapillus*), Gill et al. 1994; house mice (*Mus domesticus*), Watkins et al. 1998). Gill et al. (1995) noted that cinnamamide is unusual in being repellent to both birds and mammals.

Spurr and Porter (1998) demonstrated that captive kea and eastern rosellas (*Platycercus eximius*) ate little of carrot bait surface-coated with 0.5% cinnamamide in choice and no-choice tests. They also reported that cinnamamide mixed into cereal-based bait reduced bait consumption by weka (*Gallirallus australis*), by 31% at 0.25% and 83% at 0.5%. Cinnamamide is also repellent to a number of bird species, including rock dove (*Columbia livia*) at 1% w/w sprayed onto food pellets (Crocker et al. 1993a), with 50% reduction in food intake at 0.26% (Watkins et al. 1995); woodpigeon (*Columbia palumbus*) when sprayed on crop at 2 kg per hectare (Gill et al. 1998a); chestnut-capped blackbird (*A. ruficapillus*) at 0.8% w/w surface-coated on rice (Gill et al. 1994); rook (*Corvus frugilegus*) and chaffinch (*Fringilla coelebs*) at 0.5% w/w surface-coated on food pellets (Crocker & Reid 1993); and greenfinches (*Carduelis chloris*), blue tits (*Parus caeruleus*), and great tits (*P. major*) at 0.6% w/w surface-coated on peanuts (Gill et al. 1998b). Watkins et al. (1995) found that depression of pre-test food consumption stabilised at about 90% at cinnamamide concentrations above 0.4–0.6% w/w. However, because the primary interest in most of these trials was reduction in crop damage, effects of addition of cinnamamide to food were usually measured over several days, and data on immediate responses are lacking. Gill et al. (1994) noted birds displaying symptoms of distaste such as head shaking and gaping (suggesting primary repellence), but also post-ingestional malaise (suggesting secondary repellence).

Cinnamamide mixed into a cereal-based porridge at 0.25% was palatable to possums (McLennan, Porter and Cowan, in Spurr & Porter 1998). Cinnamamide applied to carrot bait at a concentration of 0.5% did not affect consumption (Spurr & Porter 1998). Spurr et al. (2001) tested wild and laboratory Norway rats (*R. norvegicus*) in 3-day no-choice feeding trials with cinnamamide at concentrations of 0.1% and 0.25% mixed into cereal pellet baits containing brodifacoum. Relative to rats fed bait without bird repellent, the amount of bait eaten was significantly reduced on the first test day and across all 3 days at 0.25%, but not 0.1%, cinnamamide; neither cinnamamide concentration affected bait lethality. Crocker et al. (1993b) also found cinnamamide reduced food consumption of wild Norway rats at concentrations of 0.5% mixed into ground food pellets in both two-choice and no-choice trials, although in the no-choice trial consumption had increased after 3 days. House mice (*Mus musculus*) are repelled by cinnamamide at concentrations of 0.1–0.8% w/w (Gurney et al. 1996). Watkins et al. (1998) also demonstrated long-lasting conditioned taste aversion in mice dosed with cinnamamide (160 mg per kilogram body weight) after ingestion of a novel solution of saccharin. However, in Gurney et al.'s (1996) trial, mice did not reject cinnamamide immediately but fed normally for up to 3 h, although food consumption declined thereafter, suggesting learned avoidance from a secondary repellent effect.

Consumption of seeds by the multimammate rat (*Mastomys natalensis*) was reduced by surface coating the seeds with 0.1% by wt of cinnamamide (Ngowo et al. 2005a, b). European badgers (*Meles meles*) ate less bait surface-sprayed with cinnamamide at 1% w/w than untreated pellets (Baker et al. 2005). Wood mice (*Apodemus sylvaticus*) initially reduced food consumption in no-choice trials when presented with cinnamamide-treated food at 0.8% w/w (Gurney et al. 1996). Cinnamamide (0.5%) applied as a coating to carrots markedly reduced the amount eaten by captive rabbits (*Oryctolagus cuniculus*) (McKillop et al. in Gill et al. 1995).

Most of these trials tested surface-coated baits or sprayed crops, so concentrations used are hard to relate to the New Zealand scenario where repellent would most likely be mixed into the bait. In many trials repellency was not absolute at the concentrations tested but resulted in a reduction in birds' food intake over several days – which is appropriate when the objective is to reduce crop damage but may not be desirable when the objective is to minimise bait intake to reduce risk of lethal poisoning. Cinnamamide has repellent effects for mice and rats (at least Norway rats) and a range of other mammals at concentrations above 0.25% and possibly as low as 0.1%. However, possums show no avoidance at concentrations up to 0.5%. As Spurr et al. (2001) pointed out, cinnamamide at concentrations below those likely to affect rodents has only a low repellency for birds, at least in terms of reducing daily food consumption (see above), and would thus appear unlikely to be an option by itself as a repellent for kea and other native bird species. Gill et al. (1995) suggest the mode of action of cinnamamide may differ in birds and mammals, being principally a primary repellent for birds (evoking symptoms of distaste; Gill et al. 1994) and a secondary repellent for mammals, although exceptions are noted across a range of studies of both birds and mammals. In particular, Watkins et al. (1994) found there was no effect on food consumption of mice from adding 0.65% w/w encapsulated cinnamamide compared with adding naked cinnamamide on the first day of presentation, but consumption of food with encapsulated cinnamamide declined on the second and third test days. Cinnamamide does not appear to be available as a commercial bird repellent. This may reflect both its relatively high cost and problems encountered with rapid weathering when used as a spray on crops (Cotterill et al. 2004).

Tannic acid

Tannic acid is a specific commercial form of tannin, a type of polyphenol. The chemical formula for commercial tannic acid is often given as $C_{76}H_{52}O_{46}$, which corresponds with decagalloyl glucose, but in fact it is a mixture of polygalloyl glucoses or polygalloyl quinic acid esters with the number of galloyl moieties per molecule ranging from 2 to 12, depending on the plant source used to extract the tannic acid. The most abundant polyphenols are the condensed tannins, found in virtually all families of plants, and comprising up to 50% of the dry weight of leaves. Condensed tannins provide some plants with a defence against browsing. Their consumption inhibits herbivore digestion by binding to consumed plant proteins and making them more difficult for animals to digest, and by interfering with protein absorption and digestive enzymes (www.ansci.cornell.edu/plants/toxicagents/tannin.html). Tannins are also often noted as having an astringent taste, a suggested basis for their action as a primary repellent. Hydrolised tannins, such as tannic acid, are generally thought to be more astringent than condensed tannins, such as wattle tannin (Matson et al. 2004).

Responses of kea to tannic acid have not been tested. Phenolics, including tannins, are known to be responsible for rejection of plants or plant parts by many species of birds (Crocker & Perry 1990). Condensed tannins are repellent to red-billed quelea (*Quelea quelea*) and house sparrows (*Passer domesticus*) at a concentration of 0.2% (two-choice test); 50% were repelled at 0.65% in a no-choice test (Zeinelabdin et al. 1984; Rana & Idris 1988), although in each case some repellent-treated food was still eaten. Tannic acid is repellent to house sparrows at a concentration of 2% (R.E.R. Porter, unpublished, in Spurr et al. 1995). Cockatiels (*Nymphicus hollandicus*) in two-choice tests over 3 days drank significantly less water containing tannic acid at 0.085% and 0.17% than plain water. Birds showed a less pronounced reaction to water containing condensed tannin from wattle, with a significant reduction only at c. 1.7% (Matson et al. 2004), which was attributed to the greater astringency of tannic acid versus wattle tannin. In no-choice tests, starlings (*Sturnus vulgaris*) and red-winged blackbirds (*A. phoeniceus*) showed a progressive reduction in fluid intake when 0.5% to 5% tannic acid was added to the water; red-winged blackbirds consumed more tannic acid than starlings, which was attributed to their more likely utilisation of tannin-containing foods through their granivorous feed habits (Espaillat & Mason 1990). Greig-Smith and Rowney (1987) tested house sparrows and starlings in two-choice tests over 7 days with food treated with c. 0.8% w/w tannic acid; for some test birds, the repellent-treated food was dyed blue. The addition of tannic acid resulted in progressive declines in amount of treated food eaten; for starlings and sparrows this was more pronounced when treated food was dyed (although less untreated dyed food was also eaten). Sparrows developed aversion to the tannic acid-treated food more rapidly if it was coloured than plain. These results highlight the importance of additional visual cues in conditioned aversion. The observation of declining intake of tannic acid with concentration in experimental tests is consistent with field observations showing that tannin content of fruits and grains is positively correlated with resistance to bird feeding (e.g. Mason et al. 1984). This relationship prompted the commercial development of bird-resistant crops, such as sorghum (Bullard & York 1985). However, captive silvereyes (*Zosterops lateralis*) did not avoid artificial fruit containing 5% quebracho tannin relative to untreated fruits (Stanley & Lill 2001). The lack of avoidance was attributed to the birds' swallowing the fruits whole and thus having little opportunity to discriminate. This suggestion was supported by a second trial in which very little of a cereal diet with 5% quebracho was eaten relative to untreated cereal diet.

Breeder hens (*Gallus gallus*) fed a diet with added tannic acid at 1–4% for 6 weeks showed reduced food consumption, egg production and fertility at 2% and 4% tannic acid (Blakeslee & Wilson 1979). Such effects of long-term consumption of tannic acid have been reported in a range of studies on both birds and mammals (see below) although they are probably not of concern in relation to short-term exposure from bait for possum and rat control.

There have been no direct tests of the effects of tannic acid on food consumption and feeding responses of possums.

However, many of the plants eaten in the wild by possums, particularly in Australia, have high levels of plant secondary metabolites, including condensed tannins and other phenolics, so possums are likely to have some ability to cope with such repellents. Burchfield et al. (2005) recorded an 81% reduction in consumption of a basal diet when increasing amounts of tannic acid, up to 20% wet weight, were added to it. However, initial responses to the addition of tannic acid, which began at 5%, are not reported. Concentrations of tannin and other phenolic compounds also influence food intake by free-living possums (Landsberg 1987; Pass & Foley 2000). The inclusion of 4.6% dry matter of the phenolic gallic acid into possum basal diet had little effect on food consumption; however, possums in that trial had previous experience of other plant secondary metabolites that may have influenced its acceptability (Wiggins et al. 2003). Consumption of food pellets with added 2% tannic acid by laboratory Norway rats did not differ from that of rats fed untreated food on the first day or over 3 days in a no-choice trial (Spurr et al. 1995, 2001). Similarly, groups of laboratory rats fed diets containing 0.25–2% tannic acid did not differ in food consumption, although various other measures (e.g. apparent protein digestibility, liveweight gain) reduced with increasing tannic acid concentration (Barszcz et al. 2011). More severe effects were seen in rats fed 4–8% tannic acid in a no-choice test, with 90% of rats dying in 4–6 days on a diet with 8% tannic acid (Glick & Joslyn 1970). Laboratory rats dosed with 0–0.4% tannic acid in their drinking water for 13 weeks showed no dose-related changes in food consumption or body weight gain, although a slight reduction in water intake was noted at 0.4% (Ogasawara et al. 1990).

In a food choice trial with reed voles (*Microtus fortis*), food consumption declined with increasing concentration of tannic acid up to 6% (Junnian et al. 2007). Fallow deer (*Dama dama*) drank little water containing 3.2% tannic acid compared with plain water (Bergvall 2009). Fallow deer also preferred food pellets with lower concentrations of tannic acid (0.3% and 0.65% versus 1.5%), which Bergvall and Leimar (2005) attributed to the astringent taste of tannic acid. Food consumption by plateau zokors (*Eospalax baileyi*) was not reduced by addition of 3% or 6% tannic acid although, as with rats (above), there were effects on food and protein digestibility (Lin et al. 2012). Amounts of 300 mM fructose solution drunk by the lesser mouse lemur (*Microcebus murinus*) and the bare-tailed woolly opossum (*Caluromys philander*) in choice tests declined with increasing addition of tannic acid from 0.03% to 0.22% and from 0.05% to 1.35%, respectively; for the opossum, the effect was dose related, with relative reduction greater than 80% at concentrations above 0.85% (Simmen et al. 1999). Quebracho (a condensed tannin) applied at c. 3% to twigs of apple tree reduced consumption by meadow voles (*Microtus pennsylvanicus)* by 92% measured over 5 days (Swihart 1990).

The role of tannins in defending plants against herbivores is complex, and appears to include both primary- and secondary-repellent modes of action (Robbins et al. 1987). It has also been suggested that prior experience (through feeding on tannin-containing foods) may influence subsequent response to tannins. This latter suggestion may be relevant if, for example, the diet of kea included such items. It is difficult to assess tannic acid as a potential primary repellent for kea because most experiments on other avian species measured responses over several days and immediate responses on first presentation are not reported. However, over a range of tannic acid concentrations up to 5%, intake of tannic acid-treated food or water was reduced in a dose-related manner. Long-term exposure of birds to food with >2% tannic acid appears to cause a range of harmful physiological changes, but such effects are unlikely from the short-term exposure to possum and rat bait under operational best practice. It is not clear whether such physiological changes are of a type and/or occur rapidly enough to induce the learned avoidance required for tannic acid to work effectively as a secondary repellent, although they might be sufficient in prefeed to teach animals not to eat bait. Tannic acid as a repellent has not been tested on possums, but related research on secondary compounds in possum diet suggests tannic acid is likely to impact on food consumption of possums, but at what concentration is unclear. Food consumption by Norway rats was found to be unaffected at 2% tannic acid concentration, even though some physiological changes were detected on prolonged feeding at that concentration. No-choice feeding at higher concentrations resulted in mortality. Norway rats appear more sensitive to tannic acid in water than in food, with some impact on consumption at 0.4%. No information was found about the responses of ship rats to tannic acid. Experiments on other mammals show results similar to those from Norway rats, namely a dose-related effect (with some variation between species) and a higher sensitivity to tannic acid in fluids than in food, but initial responses to tannic acid-treated material are not usually reported.

Caffeine

Caffeine is the common name for trimethylxanthine (systematic name is 1,3,7-trimethylxanthine or 3,7-dihydro-1,3,7-trimethyl-1H-purine-2,6-dione). It is produced by several plants, including coffee beans, guarana, yerba maté, cacao beans, and tea. For the plants, caffeine acts as a natural pesticide and may paralyse and kill insects that feed on them. When purified, caffeine is an intensely bitter white powder, and when consumed it is believed to exert its effects on adenosine receptors in the brain and other organs. It therefore probably has both primary and secondary repellent effects.

Responses of kea to caffeine have not been tested. Avery and Cummings (2003) tested red-winged blackbirds in no-choice trials for 4 days with rice surface-coated with 0.1% to 0.25% caffeine; there was a dose-related effect, with a 76% reduction in treated rice eaten at 0.25% caffeine. A subsequent trial (Avery et al. 2005) used the same procedure and caffeine concentrations to test responses of red-winged blackbirds and brown-headed cowbirds (*Molothrus ater*). Amount of treated food eaten by blackbirds was reduced, particularly at concentrations ≥0.15%; on the first day of presentation the reduction, however, was only c. 40%, and reductions on days 2–4 were similar. Amount of treated food eaten by cowbirds was reduced in a dose-related manner, and was 72% by day 4; at 0.15% and 0.25% caffeine, the amount of food eaten declined progressively over the four days. On the first day of presentation, the reduction at 0.25% caffeine was c. 60%. An aviary trial with a mix of blackbirds and cowbirds found that 0.25% caffeine reduced rice consumption over 3 days by c. 91%. A field trial near blackbird roosting sites using rice treated at 1% recorded a significant repellent effect that increased over the three days; on the first day feeding on treated rice was reduced by 60%. Avery et al. (2005) analysed caffeine concentrations on rice in their various trials and found it was often significantly below nominal concentration. Linz et al.

(2006) found no repellent effect of caffeine sprayed aerially on sunflower heads at a dose rate of 4.49 kg ha^{-1}, using small groups of red-winged blackbirds caged among the crop. Linz et al. (2007) tested caged blackbirds for 4 days with sunflower heads sprayed with caffeine at concentrations of 0.22%, 0.28% or 0.47%. Caffeine at all concentrations reduced damage to sunflower heads compared with untreated controls, and the reduction was greatest at the highest caffeine concentration. Werner et al. (2007) tested red-winged blackbirds in two-choice trials over 4 days using caffeine treatments of 0.025% and 1% surface coated on rice; sodium benzoate was also included in the surface coating to increase the solubility of the caffeine. Repellency was about 90% at 0.025% caffeine and 100% at 1% caffeine, both on the first day of presentation and across all four days. In a 1-day no-choice test, repellency increased from about 15% at 0.025% caffeine to 100% at caffeine concentrations from 0.5% to 2%. Werner et al. (2009a) broadcast 1% caffeine-treated and untreated rice within fallow rice fields; amount of treated rice eaten was reduced by c. 84%.

When captive possums were offered an overnight choice of plain cereal pellets and pellets containing 1.3%, 2.6% or 13% w/w caffeine, acceptance and palatability both declined with caffeine concentration relative to untreated pellets (P. Fisher, Landcare Research, Lincoln, NZ, unpubl. data). In a subsequent no-choice trial, possums offered pellets with 2% caffeine ate 32% less than those offered untreated pellets. Caffeine concentrations in pellet bait that were acceptable to captive possums were not acceptable to captive ship rats (*R. rattus*): pellets with 2% caffeine had almost zero acceptance and palatability to rats, although this improved slightly at a lower caffeine concentration of 0.2%. Encapsulation of caffeine increased acceptance and palatability to ship rats at concentrations of 0.2% and 2% (P. Fisher, unpubl. data). Caffeine is effective at inducing conditioned taste avoidance in rats when given orally (Newland & Brown 1992). White and Mason (1985) found a dose-related effect, with aversion developing after IP (intraperitoneal) caffeine doses ≥40 mg per kilogram body weight. Vishwanath et al. (2011) found no aversion in two strains of laboratory rats at IP doses of 0.32 to 3.2 mg kg^{-1} caffeine; aversion in one strain at 18 mg kg^{-1} and in both strains at 32 mg kg^{-1}. However, Massei and Cowan (2002) found no avoidance effect in rats dosed orally with 20 mg kg^{-1}. Field et al. (2010) tested house mouse and white-footed mouse (*Peromyscus leucopus*) responses to caffeine using 2-day two-choice tests; both species showed no preference at 0.06% caffeine, but avoided the caffeine solution at 0.19% and 0.97%.

Guinea pigs (*Cavia porcellus*) showed similar responses to caffeine as house and white-footed mice (Field et al. 2010). Coffee grounds are indicated on the internet as deterrent to cats, dogs, rabbits and deer (e.g. http://www.ehow.com/facts_7428761_coffee-repellent.html).

Caffeine has potential as a bird repellent, at least for crop protection. However, it appears to have been tested only on a very limited range of bird species. The limited available data suggest that 1% would be an appropriate initial level to test on kea. At that level, and up to 2%, effects on food consumption by possums appear to be minor. However, rats appear to be more sensitive to caffeine at concentrations above 0.2%, especially if exposed for more than one day (although data are limited).

Garlic oil

Garlic extract or oil is produced from garlic bulbs (*Allium sativum*). The material is usually a mixture of diallyl, dimethyl, and allyl-methyl polysulphides (Hile et al. 2004). There is some evidence that some herbivores and omnivores may avoid sulphurous odours associated with plants such as garlic (Mason & Linz 1997). While not clearly characterised, garlic oil appears to act largely as a primary repellent.

Garlic oil has not been tested as a repellent for kea. The addition of garlic oil at all concentrations from 0.01% to 1% reduced food consumption by starlings relative to untreated food over a 5-day trial; there was a slight, but non-significant effect of increasing oil concentration (Mason & Linz 1997). Repellency was also demonstrated by Hile et al. (2004) using no-choice trials, and showed a dose-response relationship. However, even at the highest concentrations tested, consumption was only reduced by 40–50%. The hourly pattern of feeding showed no evidence of a learned avoidance response (secondary repellent effect). Linz et al. (2007) found that feeding by caged red-winged blackbirds on sunflower achenes sprayed with 4% or 12% w/w garlic oil was reduced by 58% and 97%, respectively. A second trial using 2%, 1%, and 0.5% garlic oil recorded feeding reductions of 80%, 40%, and 22%, respectively. However, if only the exposed tips of the achenes were sprayed rather than the whole achene, there was no reduction in feeding.

The internet has many accounts, recipes and patents relating to the supposed efficacy of garlic as a possum repellent, but experimental evidence is generally lacking. Cooney (1998) tested 10 products (5 primary and 5 secondary repellents, concentration not stated) claimed to deter possums, including garlic spray. The repellents were sprayed on pieces of apple and offered along with untreated apple. Garlic spray was ineffective in repelling hungry possums. As for possums, the internet has many accounts, recipes and patents relating to the supposed efficacy of garlic as a rodent repellent, but experimental evidence is again lacking.

Curtis et al. (2002) tested prairie voles (*Microtus ochrogaster*) with ground-up garlic stems added to apple sauce at 14%, 25%, and 50% in one-choice feeding trials. Of the 12 species of plants tested for repellency, garlic ranked 7/12 at 14%, 10/12 at 25%, and 10/12 at 50%. There was no difference in repellency between the three concentrations of garlic stems. As for possum and rats, there are many accounts, recipes and patents relating to the supposed efficacy of garlic as a herbivore repellent (particularly for deer), but no experimental evidence.

While garlic oil appears to have some potential as a bird repellent, there is little information about its efficacy as a primary repellent. Most trials measured effects over several days (as interest was in garlic oil to protect crops) and did not report immediate responses. There is an almost complete lack of experimental information about effects of garlic oil on possums, rodents and other mammals, but anecdotal evidence does not suggest strong aversion.

Ortho-aminoacetophenone

Ortho-aminoacetophenone (OAP) is a natural product found in some varieties of grapes and in the scent gland secretions of mustelids (Acree et al. 1990 in Mason et al. 1991). It is structurally similar and has similar odour to methyl anthranilate, also found in grapes; both chemicals are known to act as bird repellents (Mason et al. 1991). Many of the reported trials do not report initial responses, but only effects over several days, making it difficult to assess the repellent potential of OAP.

Ortho-aminoacetophenone has not been tested on kea. Consumption of treated food by starlings was reduced significantly in both no-choice and choice tests at concentrations from 0.01% to 1%. There was, however, no clear dose-related response, although less treated food was eaten in two-choice trials. Wager-Page and Mason (1996) found a significant reduction in the amount of apple coated with 1% OAP eaten by starlings, but a much smaller reduction to OAP odour only, and suggested that response to OAP was most likely mediated by taste or oral trigeminal chemoreception rather than naso-trigeminal chemoreception, and so its mode of action was as a primary repellent. Starlings with no prior experience drank less water containing c. 0.4% OAP than plain water; there was almost no consumption of OAP-treated water on the first day of presentation but a small, gradual increase over the next 5 days (Clark 1996). Nicholls et al. (2000) tested 4-aminoacetophenone on American kestrels (*Falco sparverius*); it caused some food rejection but did not deter them from eating treated day-old cockerels.

Spurr et al. (2001) found laboratory Norway rats ate similar amounts of food with 1% OAP and untreated food. No data were found for ship rats. Nolte et al. (1993a, b) found strong avoidance by laboratory house mice of water with 0.25% to 1% OAP in no-choice tests. Nolte and Mason (1995) also demonstrated that the offspring of mice provided with solutions containing 0.1% OAP during pregnancy drank more of an OAP solution in no-choice tests than those of mothers provided with plain water. In that trial Nolte and Mason (1995) also found a strong dose-related response in both control and treated mice to OAP at 0.1%, 0.25% and 0.5%, as previously observed (Nolte et al. 1993a, b).

Wager-Page and Mason (1996) evaluated the effects of OAP on food consumption of prairie voles and deer mice (*Peromyscus maniculatus*); they found a generally dose-related significant reduction by both species in the amount of treated apple eaten at each concentration from 0.01% to 10% OAP.

While OAP appears to have potential as a bird repellent, the limited data on effects on possums and rats suggest further evaluation is needed of its suitability as a candidate for inclusion on cereal bait for possum and rat control.

Thiram

Thiram (tetramethylthiuram disulphide) is primarily used to prevent fungal diseases in seed and crops. It is also used as a bird and mammal repellent to protect crops, horticulture and ornamentals. Its mode of action suggests it is largely a secondary repellent, capable of inducing conditioned avoidance, and it may require repeated doses for efficacy (Kimball & Taylor 2010).

Thiram's bird repellent properties have been demonstrated in several studies (Young & Zevallos 1960; Schafer et al. 1977). Feral pigeons (*Columbia livia*) consumed less water with added thiram in a dose-related manner in no-choice tests (Duncan 1963). However, Avery and Decker (1991) found no reduction in food consumption of red-winged blackbirds in two-choice trials with thiram at 0.01%, 0.1% or 1%; in no-choice tests consumption was only reduced significantly at 1% thiram. By contrast, Werner et al. (2010) tested red-winged blackbirds with thiram at manufacturer's label rate (c. 0.08%) and found a significant reduction in treated food versus plain food both on the first presentation and over 4 days; no-choice testing demonstrated little evidence of a dose-related response from 25 to 100% of label rate, but a significant increase in repellency at 200% of label rate. Dhinsa et al. (1991) observed no reduction in seed loss to crows (*Corvus splendens*) by treating seeds with 0.5% thiram. However, Kennedy and Connery (2008) found thiram at 0.1–0.8% provided the best control of rook damage to seeds and seeding of winter and spring wheat, with a dose-response effect. Lopez-Antia et al. (2014) found red-legged partridges (*Alectoris rufa*) ate less 0.175% thiram-treated food than plain food in a no-choice test; the effect was most pronounced on the first day and declined over the next 3 days. In a subsequent two-choice test little thiram-treated seed was eaten on any of the 4 days.

Repellency of thiram to mammals appears to be variable. It has been reported to repel laboratory Norway rats (Bellack et al. 1953, in Radwan 1969), ship rats (Dalmacio 1969, in Meehan 1988), and a range of other rodents (Welch 1954). Thiram (as Thiroprotect – 8% active) is marketed as a repellent for possums in New Zealand and reduced damage to sprayed seedlings by possums over a 7-day period (D. Morgan, Landcare Research, Lincoln, NZ, pers. comm.). Surface coating cardboard cartons with 1.5% and 4.5% thiram significantly reduced the number of visits to the cartons and extent of damage to the cartons by ship rats and Indian mole rats (*Bandicota bengalensis*) (Parshad et al. 1993).

Thiram is also repellent to a number of small mammal species. Zurcher et al. (1983) found that thirteen-lined ground squirrels (*Spermophilus tridecemlineatus*) ate little seed treated with 0.08% thiram compared with untreated seed, and seeds treated with 0.16% or 0.32% thiram were eaten less than seeds treated with lower thiram concentrations. When only 0.08%-treated seed was provided, squirrels ate normal daily amounts and maintained body weight. Johnson (1985) also found applications of 0.08% to 0.8% thiram were ineffective in reducing squirrel seed consumption, but 1.25% thiram was repellent, whereas deer mice were repelled by 0.31% and 1.25% thiram. Swihart (1990) found that meadow voles were repelled from eating apple tree twigs by 1.4% thiram whether or not alternative food was available. Thiram at 1% was successful at reducing loss of maize seed caused by multimammate rats (Ngowo et al. 2005a, b). Seeds coated with thiram at 16.7% suffered significantly less damage by house mice and deer mice than untreated seeds (Nolte & Barnett 2000). Rabbit browsing damage on seedlings of several tree species was reduced after application of a commercial product containing thiram at concentrations of 7% to 20% (Boggess 1981). Detour, a commercial repellent containing 7% thiram, significantly reduced damage by mule deer (*Odocoileus hemionus*) to seedlings sprayed at specified label application rate compared with untreated controls (Wagner & Nolte 2001). However, Kimball et al. (2009) found thiram ineffective against white-tailed deer (*Odocoileus virginianus*) in short-term tests, but pointed out that avoidance of thiram usually takes several exposures to develop.

Thiram appears to repel a wide range of small mammal species at concentrations effective for repelling birds, so it does not appear to be a suitable candidate for inclusion on cereal bait for possum and rat control.

Formulation issues

In addition to efficacy as a repellent, a suitable compound has to be able to withstand the cereal pellet manufacturing process, in which high temperatures from superheated steam are probably the main issue, as well as storage at room temperature for up to 12 weeks after manufacture. A preliminary assessment of stability was made for tannic acid, ortho-aminoacetophenone (OAP), and garlic oil based on their known chemical characteristics.

Tannic acid (CAS No. 1401-55-4) is a yellowish-tan powder that is stable under normal conditions. It is soluble in water (2850 g L^{-1}). It is incompatible with salts of heavy metals, strong oxidisers, lime water, albumin, gelatine, and alkaloids. It has a flash point of 198°C and a melting point of 210°C. It is not volatile and boiling point is not applicable. It is air, moisture, and light sensitive. These characteristics suggest it is likely to be stable in bait and unaffected by heat or volatility issues in the bait manufacture process.

2-aminoacetophenone (CAS No. 551-93-9) is a yellow oily liquid that is stable at room temperature under normal conditions. It is slightly soluble in water. It has a melting point of 20°C, and a boiling point of 252°C, vapour pressure 0.02 mm Hg at 25°C, vapour density of 4.66, flash point of 106°C, it is incompatible with oxidisers, and is steam volatile. The recommended storage temperature is 2–6°C. Based on these characteristics it may not be stable in bait.

Garlic oil (CAS No. 8000-78-0) is a yellowish liquid that is soluble in water. It is stable but heat should be avoided. There is no information on its stability under different temperatures. Garlic oil blends well with ethanol, ether, benzene and other organic solvents. An essential oil like garlic oil is likely to be volatile and susceptible to heat in the bait manufacturing process.

A potential benchmark for an acceptable cost of adding bird repellent to cereal bait for possum and rat control is the cost of deer repellent, although its cost limits its use currently to operations that aim to minimise deer by-kill. The addition of deer repellent doubles the price of cereal bait (i.e. its cost is about $2.50 per kilogram of bait). Potential costs of tannic acid, OAP, and garlic oil at concentrations likely to be effective as bird repellents were sourced through an internet search of chemical suppliers (Table 1). With the possible exception of OAP at 1%, potential increases in bait cost would likely be lower than the current additional cost of deer repellent.

Table 1. Likely costs of bird repellent (indicative prices from www.alibaba.com) and consequent potential increase in cost of bait.

Repellent	Cost/kg (estimate)	Potential concentration in bait	Cost per kg of bait (% increase)
Tannic acid	c. $50	2–4%	$1–$2 (40–80%)
Ortho-aminoacetophenone	$100–$500	0.25–1%	$0.25–$5 (10–300%)
Garlic oil	c. $20	2%	c. $0.40 (16%)

Potential repellents for kea

A recent review of the avian taste system (Roura et al. 2013) concluded that birds have a well-developed taste system, with genome sequencing suggesting taste genes for umami, sour, salt, bitter, calcium, and lipids. However, the review also concluded that the avian taste system differs significantly between species, suggesting that experimental assessment of compounds as repellents for kea will be necessary, at least in the short term, and that what is repellent to kea may not be effective on other New Zealand native bird species. Kea have also demonstrated an ability to distinguish between test scents and experimental control compounds and to detect novel scents (Gsell et al. 2012), so odours related to pest control baits may also play a role in, or be able to be exploited to, promote avoidance learning.

While caffeine may be a suitable compound to test on kea for repellency, its probable repellent effects on rats at concentrations below those effective for kea suggest it will not be useful for inclusion in possum and rat bait. Although thiram is thought to be a secondary repellent, several studies suggest repeated consumption is required for avoidance to develop fully. That could limit its usefulness as a repellent for kea and other native bird species, as repeated consumption of bait is likely to be undesirable. It also appears to repel a wide range of mammals. Thiram does not, therefore, appear suitable for further consideration for a kea-repellent bait. The few available data on cinnamamide suggest that at concentrations of at least 0.5% there may be initial rejection of surface-coated food by kea, and this is supported by similar observations on other bird species. However, at that concentration cinnamamide appears likely to reduce food consumption by Norway rats and mice (no data were found for ship rats) and some other small mammals, but unlikely to affect food consumption by possums. In addition, the mode of action of cinnamamide requires further clarification, particularly in light of the suggestion that it may differ between birds and mammals. Cinnamamide, used alone, does not therefore appear to be a suitable candidate for further evaluation.

As Spurr et al. (2001) noted previously, information on initial responses of birds and mammals to adding tannic acid to food is sparse. It is also not clear if tannic acid exerts its effect solely as a primary (taste) repellent or if it also has secondary repellent effects, depending on concentration. Assessing its potential usefulness would require trials of kea, possums, and ship rats. Spurr et al. (2001) suggested a priority was to establish the length of time that tannic acid is repellent to birds. Based on previous research on other species, concentrations of 2% and 4% tannic acid should be used for any future initial evaluations – 2% as that concentration appears to repel sparrows but not rats, and 4% if there is a need to increase primary repellent effect on kea. Tannic acid appears unlikely to have any problems with regard to bait manufacture, and its cost is likely to be acceptable to management agencies.

Spurr et al. (2001) recommended that further research was needed to establish optimal concentrations of OAP to be added to bait, particularly the highest concentrations palatable to rats still repellent to birds. Spurr et al. (2001) did not refer to the studies on mice and other small mammals (above) suggesting OAP may be repellent to small mammals at concentrations likely to be repellent to birds. Further evaluation of different concentrations of OAP on possums, rats and mice is therefore warranted, as well as the responses of kea. However, there is a suggestion that OAP may not be stable in the bait manufacturing process and, depending on concentration, its cost may be higher than other alternatives.

If garlic oil was to be tested on kea, 2% is probably an appropriate starting concentration, based on Linz et al. (2007). Its cost would be acceptable to management agencies, but as with OAP, its stability during bait manufacture would need to be confirmed.

Taking into account the available information on effects on birds and mammals, and formulation requirements and cost, tannic acid is considered the highest priority for further testing. One caveat to that recommendation is the limited available information on toxicity of each of the compounds. For laboratory rats dosed by oral gavage with tannic acid, the LD50 is 2230 mg kg^{-1} (Boyd et al. 1965); the only avian data (for red-winged blackbirds) suggest an oral LD50 of >100 mg kg^{-1} (Schafer et al. 1983). For garlic oil the oral LD50 for rats and mice is recorded as 1360 and 850 mg kg^{-1}, respectively (Sweet 2012). Surprisingly, no toxicity data were found for OAP, although it is used as a food additive. Also relevant to choice of compound and concentration is the maximum concentrations that would trigger a hazard classification for non-toxic bait for possum and rat control or alter the hazard classification for toxic bait and consequently require reassessment by the relevant regulatory authority. For New Zealand, the initial concentrations under consideration for tannic acid and OAP would not trigger reassessment, but garlic oil probably would, as the suggested trial concentration of 2% would be more than double the concentration allowed by the current approvals.

A useful trial design for testing tannic acid on possums and rats would be the one used by Cowan et al. (2015) – a two-choice trial that mimics aerial poisoning with 3 days' choice of plain and treated food, 5 days' plain food, and a final 2 days' choice of plain and treated food. That protocol allows evaluation of both initial response and learned avoidance. If tannic acid proved suitable in that test, additional assessment of the effects on captive possum and rats of its inclusion in toxic bait would be required, before proceeding to field trials.

There is also scope for further evaluation of anthraquinone as a repellent. The trials by Cowan et al. (2015) and Clapperton et al. (2015) suggest a concentration between 0.04% and 1% may be acceptable to rats. This research could be progressed by determining the maximum concentration acceptable to rats and assessing its efficacy in repelling kea from bait with surface-coated or incorporated anthraquinone. Results from these trials also suggested a possible effect of d-pulegone inclusion on increasing the palatability of bait with anthraquinone, at least at lower concentrations; this requires further investigation.

Relevance for other native birds

The availability of a suitable repellent for kea would likely have benefits for at least some of the other vulnerable native bird species, although there may be species differences in responses (Roura et al. 2013). For example, Werner et al. (2009b) found significant differences between three bird species in the threshold concentration for avoidance of anthraquinone-treated food and Zungu and Downs (2015) found similar species differences in response to tannin-treated food.

Of the 19 species of native birds found dead after 1080 possum control operations (Spurr 2000), eleven have been recorded after operations using cereal pellets (Veltman & Westbrooke 2011; Fairweather et al. 2014), ranging in adult body weight from 11g (tomtit, *P. macrocephala*) to 2–3 kg (kiwi, *Apteryx* spp.). Even with the inclusion of repellents, smaller birds will probably remain at greater risk of poisoning, because they need to eat much less bait to be killed and they may access bait both by pecking at large pellets and by feeding on small pieces resulting from bait fragmentation during aerial delivery (Nugent et al. 2011) or from waste from feeding by target species. For example, the LD_{50} for a female tomtit is contained in about 0.08 g of a cereal pellet with 0.15% 1080 (Fairweather et al. 2014). Thus individual repellents or repellent combinations will need to be highly effective to protect smaller native species. Although some native birds have been tested for their responses to baits used for possum control with added flavourings (e.g. Udy & Pracy 1981; Spurr 1993) the only native birds other than kea on which known repellents (d-pulegone and anthraquinone) have been tested are the North Island robin (*P. macrocephala longipes*) and tomtit (*P. macrocephala toitoi*) (Day et al. 2003; Clapperton et al. 2014). Surface spraying with or dipping the baits in repellents reduced but did not eliminate pecking at the baits, although pecking did not always result in feeding and it declined over the 4 days of the trials. Day et al. (2003) commented that the level of pecking observed may have resulted in some deaths of robins had the baits been toxic. Clapperton et al. (2014) found a similar but greater reduction in pecking of baits soaked in repellent (0.09% anthraquinone), although avoidance may have been enhanced by the inclusion of blue dye in the baits (Clapperton et al. 2011). Blue dye may be less attractive to some birds than the green dye used in operational control baits (Hartley et al. 1999).

Strategies for repellent testing and use

There have been various attempts to develop systematic approaches to the identification of suitable compounds for testing as bird repellents. These have included, for example, screening large numbers of compounds on captive birds (Schafer et al. 1983; Clark 1995); consideration of taxonomic differences (Mason et al. 1992); new methodologies such as cell culture techniques for more rapid screening of candidate primary repellents (Bryant et al. 2000) and the incorporation in bait of ultraviolet cues to facilitate avoidance learning (Werner et al. 2104); and predictive structure-activity models (Clark & Shah 1991; Clark et al. 1991; Watkins et al 1999). Despite the potential advantages such structured approaches may offer (Clark 1998) and new insights into the responses of birds to sensory cues (Clark 2014; Werner et al. 2014), most of the recently published experimental trials of bird repellents internationally have focussed on further testing or enhancement of a few reasonably well characterised compounds, particularly anthraquinone, d-pulegone, and methyl anthranilate (e.g. Carlson et al. 2013; Esther et al. 2013; Tupper et al. 2014; Werner et al. 2015). The main reason for this appears to be a focus on repellents that are already registered for use, given the very high cost of registering novel products (Eisemann et al. 2011). The immediate issue of risk to kea and other native birds has also dictated the need for rapid solutions, which has directed the focus towards existing compounds.

In aerial poisoning operations with prefeeding (which is the most common procedure for possum and rat control in New Zealand), birds show one of four behaviours: (1) ignore all bait; (2) eat prefeed but not toxic bait; (3) do not eat prefeed but eat toxic bait; and (4) eat prefeed and toxic bait.

Minimising non-target deaths requires a strategy to minimise type (3) and (4) responses. To mitigate mortality risk to type (3) responders, a primary repellent would be needed in toxic bait. The potential strategy for type 4 responders is more complex; it could involve the same or different primary repellents in prefeed and toxic bait; a secondary repellent with appropriate cues for avoidance learning in prefeed and a primary repellent with the same cues in toxic bait; or both primary and secondary repellents in prefeed with appropriate cues for avoidance learning and a primary repellent with the same cues in toxic bait. A secondary repellent in prefeed and primary repellent in toxic bait provides the opportunity for a learned response to the secondary repellent for those birds that eat sufficient prefeed and unlearned response to primary repellent for those birds that do not eat prefeed or eat insufficient to induce an avoidance response. However, if the primary repellent is highly effective, a mixture of primary and secondary repellents in prefeed may reduce the probability that birds that eat prefeed eat enough to develop conditioned avoidance to the secondary repellent. Another risk with a mix of primary and secondary repellents in prefeed is that the learning cues provided by current bait (e.g. green dye, cinnamon and primary repellent) may be insufficient or confusing for the development of effective conditioned avoidance. However, various studies have shown that combinations of repellent stimuli may be more effective at deterring birds than single repellents and that initial exposure to a primary repellent followed by avoidance learning to a secondary repellent may enhance repellency or allow reduced repellent application rates (e.g. Avery & Mason 1997; Clapperton et al. 2011, 2014; Day et al. 2012; Werner & Provenza 2011). Such a strategy may be applicable to protecting New Zealand birds, but it will require extensive testing to identify combinations and concentrations appropriate to deter birds from feeding but not possums and rats.

Operationally, inclusion of repellent into bait during manufacture would be preferable since that would enable production of a consistent product. However, for small birds like robins and tomtits that peck at bait, surface coating might provide greater protection as the repellent would be concentrated in the outer layers of the bait. Tupper et al. (2014) found that anthraquinone was effective at repelling European starlings (*Sturnus vulgaris*) when applied topically to a pellet matrix but not when incorporated into the pellet matrix even at a much higher concentration. However, the increased costs involved in surface coating may be an issue. The additional costs associated with surface coating cereal bait for possum control with deer repellent (Morriss 2007) approximately doubles the cost of bait.

Current research on repellents for native bird protection in New Zealand is driven in part by the need for timely practical solutions. However, increased understanding from genetic and physiological studies on the visual, olfactory, and taste senses of birds and their differences from mammals (Roura et al. 2013; Clark 2014) should facilitate the identification of more effective repellents and more effective strategies for their use, extending to the inclusion of other sensory cues, masks or attractants designed to maximise repellent efficacy for birds while minimising it for target mammals (Clapperton et al. 2015).

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References

Avery ML, Cummings JL 2003. Chemical repellents for reducing crop damage by blackbirds. Proceedings of a special symposium of the Wildlife Society 9th Annual Conference, Bismark, Dakota, 27 September 2003. Pp. 42–48.

Avery ML, Decker DG 1991. Repellency of fungicidal rice seed treatments to red-winged blackbirds. Journal of Wildlife Management 55: 327–334.

Avery ML, Mason JR 1997. Feeding responses of red-winged blackbirds to multisensory repellents. Crop Protection 16: 159–164.

Avery ML, Werner SJ, Cummings JL, Humphrey JS, Milleson MP, Carlson JC, Primus TM, Goodall MJ 2005. Caffeine for reducing bird damage to newly seeded rice. Crop Protection 24: 651–657.

Baker SE, Ellwood SA, Watkins R, Macdonald DW 2005. Non-lethal control of wildlife: using chemical repellents as feeding deterrents for the European badger *Meles meles*. Journal of Applied Ecology 42: 921–931.

Barszcz, M, Taciak M, Skomial J 2011. A dose-response effect of tannic acid and protein on growth performance, caecal fermentation, colon morphology, and β-glucuronidase activity of rats. Journal of Animal and Feed Sciences 20: 613–625.

Bergvall UA 2009. Development of feeding selectivity and consistency in food choice over 5 years in fallow deer. Behavioral Processes 80: 140–146.

Bergvall UA, Leimar O 2005. Plant secondary compounds and the frequency of food types affect food choice by mammalian herbivores. Ecology 86: 2450–2460.

Blakeslee JA, Wilson HR 1979. Response of hens to various dietary levels of tannic acid. Poultry Science 58: 255–256.

Boggess EK 1981. Repellents for deer and rabbits. Great Plains Wildlife Damage Control Workshop Proceedings, Paper 113. Pp 171–177.

Boyd EM, Bereczky K, Godi I 1965. The acute toxicity of tannic acid administered intragastrically. Canadian Medical Association Journal 92: 1292–1297.

Bryant BP, Savchenko A, Clark L, Mason RJ 2000. Potential for cell culture techniques as a wildlife management tool for screening primary repellents. International Biodeterioration and Biodegradation 45: 175–181.

Bullard RW, York JO 1985. Breeding for bird resistance in sorghum and maize. In: Russell GE ed. Plant breeding progress reviews 1. London, Butterworths. Pp. 193–222.

Burchfield E, Agara NS, Hume ID 2005. Effects of terpenes on some physiological and biochemical parameters in two species of phalangerid possums (Marsupialia:

Phalangeridae). Australian Journal of Zoology 53: 395–402.
Carlson JC, Tupper SK, Werner SJ, Pettit SE, Santer MM, Linz GM 2013. Laboratory efficacy of an anthraquinone-based repellent for reducing bird damage to ripening corn. Applied Animal Behaviour Science 145: 26–31
Clapperton BK, Porter RER, Day TM, Waas JR, Matthews LR 2011. Designer repellents: combining olfactory, visual or taste cues with a secondary repellent to deter free-ranging house sparrows from feeding. Pest Management Science 68: 870–877.
Clapperton BK, Morgan DKJ, Day TD, Oates KE, Beath AM, Cox NR, Matthews LR 2014. Efficacy of bird repellents at deterring North Island robins (*Petroica australis longipes*) and tomtits (*P. macrocephala toitoi*) from baits. New Zealand Journal of Ecology 38: 116–123.
Clapperton BK, Day TD, Morgan DKJ, Huddart F, Cox N, Matthews LR 2015. Palatability and efficacy to possum and rats of pest control baits containing bird repellents. New Zealand Journal of Zoology (http://dx.doi.org/10.1080/03014223.2015.1029496).
Clark L 1995. A review of the bird repellent effects of 117 carbocyclic compounds. In: Mason JR ed. Proceedings of the Repellents in Wildlife Management Conference, Ft Collins, Colorado. Pp. 343–352.
Clark L 1996. Trigeminal repellents do not promote conditioned odor avoidance in European starlings. Wilson Bulletin 108: 36–52.
Clark L 1998. Review of bird repellents. In: Baker RO, Crabb AC eds Proceedings of the Eighteenth Vertebrate Pest Conference, University of California, Davis, CA. Pp. 330–337.
Clark L 2014. The chemical senses of birds. In: Scanes PD ed. Sturkie's avian physoiology. 6th edn. New York, Academic Press. Pp. 89–111. http://works.bepress.com/larry_clark/58 (accessed 10 August 2015).
Clark L, Shah PS 1991. Nonlethal bird repellents: in search of a general model relating repellency and chemical structure. Journal of Wildlife Management 55: 538–545.
Clark L, Mason JR, Shah PS 1991. Chemical repellency in birds: relationship between chemical structure and avoidance response. Journal of Experimental Zoology 260: 310–322.
Cooney J 1998. An evaluation of commonly used deterrents for urban common brushtail possums, *Trichosurus vulpecula* (Kerr 1792). Unpublished BSc (Hons) thesis, Deakin University, Melbourne. (summarised at www.depi.vic.gov.au/home by search for possums/possum-repellents).
Cotterill JV, Nadian AK, Cowan DP 2004. Improving the persistence of a formulation of the avian repellent cinnamamide, for the protection of autumn-sown oilseed rape. Pest Management Science 60: 1019–1024.
Cowan P, Brown S, Forrester G, Booth L, Crowell M 2015. Bird-repellent effects on bait efficacy. Pest Management Science 71: 1075–1081.
Crocker DR, Perry SM 1990. Plant chemistry and bird repellents. Ibis 132: 300–308.
Crocker DR, Reid K 1993. Repellency of cinnamic acid derivatives to rooks and chaffinches. Wildlife Society Bulletin 21: 456–460.
Crocker DR, Perry SM, Wilson M, Bishop JD, Scanlon CB 1993a. Repellency of cinnamic acid derivatives to captive rock doves. Journal of Wildlife Management 57: 113–122.
Crocker DR, Scanlon CB, Perry SM 1993b. Repellency and choice; feeding responses of wild rats (*Rattus norvegicus*) to cinnamic acid derivatives. Applied Animal Behaviour Science 38: 61–66.
Crowell M, Booth L, Cowan P, Fairweather A, Westbrooke I 2015a. Stability of bird repellents used to protect kea (*Nestor notabilis*) during aerial 1080 cereal operations. New Zealand Journal of Ecology 40: 42–48.
Crowell M, Martini M, Moltchanova E 2015b. Effect of the addition of bird repellents used to protect kea (*Nestor notablis*) during aerial 1080 cereal operations. New Zealand Journal of Ecology 40: 49–59.
Cummings JL, Pochop PA, Davis JE Jr, Krupa HW 1995. Evaluation of REJEX-IT AG-36 as a Canada goose grazing repellent. Journal of Wildlife Management 59: 47–50.
Curtis PD, Rowland Ed, Good GL 2002. Developing a plant-based vole repellent: screening of ten candidate species. Crop Protection 21: 299–306.
Day TD, Matthews LR, Waas JR 2003. Repellents to deter New Zealand's North Island robin *Petroica australis longipes* from pest control baits. Biological Conservation 114: 309–316.
Day TD, Clapperton BK, Porter RER, Waas JR, Matthews LR 2012. Responses of free-ranging house sparrows to feed containing primary and secondary repellents. New Zealand Journal of Crop and Horticultural Science 40: 127–138.
Dhinsa MS, Sandhu PS, Saini HK, Toor HS 1991. House crow damage to sprouting sunflower. Tropical Pest Management 37: 179–181.
Dolbeer RE, Avery ML, Tobin ME 1994. Assessment of hazards to birds from methiocarb applications to fruit crops. Pesticide Science 40: 147–161.
Duncan CJ 1963. The response of the feral pigeon when offered the active ingredients of commercial repellents in solution. Annals of Applied Biology 51: 127–134.
Eisemann JD, Werner SJ, O'Hare JR 2011. Registration considerations for chemical bird repellents in fruit crops. Outlooks on Pest Management 22: 87–91.
Espaillat JE, Mason JR 1990. Differences in taste preference between red-winged blackbirds and European starlings. Wilson Bulletin 102: 292–299.
Esther A, Tilcher R, Jacob J 2013. Assessing the effects of three potential chemical repellents to prevent bird damage to corn seeds and seedlings. Pest Management Science 69: 425–430.
Fairweather AAC, Broome KG, Fisher P 2014. Sodium fluoroacetate. Pesticide information review. Version 2014/3. Unpublished report DOCDM-25427. Hamilton, New Zealand, Department of Conservation. 112 p.
Field KL, Beauchamp GK, Kimball BA, Mennella JA, Bachmanov AA 2010. Bitter avoidance in Guinea pigs (*Cavia porcellus*) and mice (*Mus musculus* and *Peromyscus leucopus*). Journal of Comparative Psychology 124: 455–459.
Fisher P, Nugent G, Morgan D, Warburton B, Cowan P, Duckworth J 2011. Possum management using aerial 1080 – not new, definitely improved. New Zealand Journal of Forestry 56: 5–8.
Gill EL, Serra MB, Canavellis SB, Feare CJ, Zaccagnini ME, Nadian AK, Heffernan ML, Watkins RW 1994. Cinnamamide prevents captive chestnut-capped blackbirds (*Agelaius ruficapillus*) from eating rice. International Journal of Pest Management 40: 195–198.
Gill EL, Watkins RW, Gurney JE, Bishop JD, Feare CJ 1995. Cinnamamide: a nonlethal chemical repellent for birds and

mammals. National Wildlife Research Center Repellents Conference, Paper 19. Pp. 43–51.

Gill EL, Watkins RW, Cowan DP, Bishop JD, Gurney JE 1998a. Cinnamamide, an avian repellent, reduces woodpigeon damage to oilseed rape. Pesticide Science 52: 159–164.

Gill El, Feare CJ, Cowan DP, Fox SM, Bishop JD, Langton SD, Watkins RW, Gurney JE 1998b. Cinnamamide modifies foraging behaviours of free-living birds. Journal of Wildlife Management 62: 872–884.

Glick Z, Joslyn MA 1970. Food intake depression and other metabolic effects of tannic acid in the rat. Journal of Nutrition 100: 509–515.

Greig-Smith PW, Rowney CM 1987. Effects of colour on the aversions of starlings and house sparrows to five chemical repellents. Crop Protection 6: 402–409.

Gsell AC, Hagelin JC, Brunton DH 2012. Olfactory sensitivity in Kea and Kaka. Emu 112: 60–66.

Gurney JE, Watkins RW, Gill EL, Cowan DP 1996. Non-lethal mouse repellents; evaluation of cinnamamide as a repellent against commensal and field rodents. Applied Animal Behaviour Science 49: 353–363.

Hartley LJ, O'Connor CE, Waas JR, Matthews LR 1999. Colour preferences in North island robins (*Petroica australis*); implications for deterring birds from poisonous baits. New Zealand Journal of Ecology 23: 255–260.

Hile AG, Shan Z, Zhang S-Z, Block E 2004. Aversion of European starlings (*Sturnus vulgaris*) to garlic oil treated granules: garlic oil as an avian repellent. Garlic oil analysis by nuclear magnetic resonance spectroscopy. Journal of Agricultural and Food Chemistry 52: 2192–2196.

Johnson RJ 1985. Repellents for rodents in conservation-tillage agriculture. Proceedings of the Second Eastern Wildlife Damage Control Conference, paper 29. Pp. 66–72.

Junnian L, Jike L, Shuanglun T 2007. Effects of hunger and tannic acid on food intake and foraging behaviour in *Microtus fortis.* Acta Ecologica Sinica 27: 4478–4484 [abstract].

Kennedy TF, Connery J 2008. An investigation of seed treatments for the control of crow damage to newly-sown wheat. Irish Journal of Agricultural and Food Research 47: 79–91.

Kimball BA, Taylor JD 2010. Mammalian herbivore repellents: tools for altering plant palatability. Outlooks on Pest Management 21: 181–187.

Kimball BA, Taylor J, Perry KR, Capelli C 2009. Deer responses to repellent stimuli. Journal of Chemical Ecology 35: 1461–1470.

King CM ed. 2005. The handbook of New Zealand mammals. 2nd edn. Melbourne, Victoria, Oxford University Press.

Landsberg J 1987. Feeding preferences of common brushtail possums, *Trichosurus vulpecula*, on seedlings of a woodland eucalypt. Australian Wildlife Research 14: 361–369.

Lin G-H, Xie J-X, Cui X-F, Nevo E, Su J-P, Zhang T-Z 2012. Effects of supplementary dietary tannic acid on digestion in plateau zokors (*Eospalax baileyi*). Annals Zoologica Fennici 49: 371–377.

Linz GM, Homan HJ, Slowik AA, Penry LB 2006. Comparison of Lorsban-4E and caffeine aerially sprayed on sunflower plots for bird repellency. National Sunflower Association Research Forum, Bismark, ND. 4 p.

Linz GM, Homan HJ, Penry LB, Primus TM, Goodall MJ 2007. Evaluation of caffeine and garlic oil as bird repellents. National Sunflower Association Research Forum, Bismark, ND. 4 p.

Lopez-Antia A, Ortiz-Santaliestra ME, Mateo R 2014. Experimental approaches to test pesticide-treated seed avoidance by birds under a simulated diversification of food sources. Science of the Total Environment 496: 179–187.

Mason JR, Linz G 1997. Repellency of garlic extract to European starlings. Crop Protection 16: 107–108.

Mason JR, Dolbeer RA, Arzt AH, Reidinger RF, Woronecki PP 1984. Taste preferences of male redwinged blackbirds among dried samples of ten corn hybrids. Journal of Wildlife Management 48: 611–616.

Mason JR, Clark L, Shah PS 1991. Ortho-aminoacetophenone repellency to birds: similarities to methyl anthranilate. Journal of Wildlife Management 55: 334–340.

Mason JR, Clark L, Shah PS 1992. Taxonomic differences between birds and mammals in their responses to chemical irritants. In: Mullet-Schwarze D ed. Chemical signals in vertebrates VI. New York, Plenum Press. Pp. 311–317.

Massei G, Cowan DP 2002. Strength and persistence of conditioned taste aversion in rats: evaluation of 11 potential compounds. Applied Animal Behaviour Science 75: 249–260.

Matson KD, Millam JR, Klasing KC 2004. Cockatiels (*Nymphicus hollandicus*) reject very low levels of plant secondary compounds. Applied Animal Behaviour Science 85: 141–156.

Meehan AP 1988. Chemical repellents. In: Prakash I ed. Rodent pest management. Boca Raton, FL, USA, CRC Press. Pp. 399–406.

Morriss G 2007. EPRO deer repellent baits for possum control: review of development and use 2001–2007. Lincoln, Landcare Research. http://www.envirolink.govt.nz/PageFiles/334/291-WCRC33.pdf (accessed 10 August 2015).

Newland MC, Brown K 1992. Oral caffeine consumption by rats: the role of flavour history, concentration, concurrent food, and an adenosine agonist. Pharmacology, Biochemistry and Behavior 42: 651–659.

Ngowo V, Mulungu LS, Lodal J, Makundi RH, Massawe AW, Leirs H 2005a. Evaluation of thiram and cinnamamide for protection of maize seeds against multimammate mice, *Mastomys natalensis*, in Tanzania. Belgian Journal of Zoology 135: 179–181.

Ngowo V, Lodal J, Mulungu LS, Makundi RH, Massawe AW, Leirs H 2005b. Evaluation of thiram and cinnamamide as potential repellents against maize-seed depredation by the multimammate rat, *Mastomys natalensis*, in Tanzania. In: Singleton GR, Hinds LA, Krebs CJ, Spratt DM eds Rats, mice and people: rodent biology and management. Canberra, Australian Centre for International Agricultural Research. Pp. 260–261.

Nicholls MK, Love OP, Bird D 2000. An evaluation of methyl anthranilate, aminoacetophenone, and unfamiliar coloration as feeding repellents to American kestrels. Journal of Raptor Research 34: 311–318.

Nolte DL, Barnett JP 2000. A repellent to reduce mouse damage to longleaf pine seed. International Biodeterioration and Biodegradation 45: 169–174.

Nolte DL, Mason JR 1995. Maternal ingestion of ortho-aminoacetophenone during gestation affects intake by offspring. Physiology & Behavior 58: 925–928.

Nolte DL, Mason JR, Clark L 1993a. Avoidance of bird repellents by mice. Journal of Chemical Ecology 19: 427–432.

Nolte DL, Mason JR, Clark L 1993b. Nonlethal rodent repellents: differences in chemical structure and efficacy from non-lethal bird repellent. Journal of Chemical Ecology 19: 2019–2027.

Nugent G, Morgan D, Clayton R, Warburton B 2011. Improving the efficacy of aerial poisoning of brushtail possums *Trichosurus vulpecula* through reduced fragmentation of bait. International Journal of Pest Management 57: 51–59.

Nugent G, Warburton B, Thomson C, Cross ML, Coleman MC 2012. Bait aggregation to reduce cost and toxin use in aerial 1080 baiting of small mammal pests in New Zealand. Pest Management Science 68: 1374–1379.

Ogasawara H, Todate A, Onodera H, Matsishima Y, Shibutani M, Yoshida J, Maekawa A, Mayashi Y 1990. Subchronic oral toxicity study of tannic acid in F344 rats. Eisei Shikenjo Hokoku 108: 84–89 [abstract].

Orr-Walker T, Adams NJ, Roberts LG, Kemp JR, Spurr EB 2012. Effectiveness of the bird repellents anthraquinone and d-pulegone on an endemic New Zealand parrot, the kea (*Nestor notabilis*). Applied Animal Behaviour Science 137: 80–85.

Parshad VR, Saini MS, Jindal S 1993. Repellent action of two fungicides against house rat *Rattus rattus* and the Indian mole rat *Bandicota bengalensis*. International Biodeterioration and Biodegradation 31: 77–82.

Pass GJ, Foley WJ 2000. Plant secondary metabolites as mammalian feeding deterrents: separating the effects of the taste of salicin from its post-ingestive consequences in the common brushtail possum (*Trichosurus vulpecula*). Journal of Comparative Physiology B 170: 185–192.

Porter RER 1977. Methiocarb protects sprouting peas from small birds. New Zealand Journal of Experimental Agriculture 5: 335–338.

Radwan MA 1969. TMTD wild mammal repellent; review and current status. Forest Science 15: 439–445

Rana BD, Idris M 1988. Laboratory evaluation of repellent property of tannin against *Passer domesticus*. Pavo 26: 33–36.

Robbins CT, Mole S, Hagerman AE, Hanley TA 1987. Role of tannins in defending plants against ruminants; reduction in dry matter digestibility. Ecology 68: 1606–1615.

Roura E, Baldwin MW, Klasing KC 2013. The avian taste system: Potential implications in poultry nutrition. Animal Feed Science and Technology 180: 1–9.

Schafer EW Jr, Brunton RB, Lockyer NF 1977. Learned aversion in wild birds: a method for testing comparative acute repellency. In: Jackson WB, Marsh RE eds. Test methods for vertebrate pest control and management materials. American Society for Testing and Materials Special Technical Publication 625. Philadelphia, PA, ASTM. Pp. 186–194.

Schafer EW Jr, Bowles WA Jr, Hurlbut J 1983. The acute oral toxicity, repellency, and hazard potential of 998 chemicals to one or more species of wild and domestic birds. Archives of Environmental Contamination and Toxicology 12: 355–382.

Simmen B, Josseaume B, Atramentowicz M 1999. Frugivory and taste responses to fructose and tannic acid in a prosimian primate and a didelphid marsupial. Journal of Chemical Ecology 25: 331–346.

Singla N, Parshad VR 2007. Antifeeding effects of a neem (*Azadirachta indica*)-based formulation botanical bird repellent against the house rat (*Rattus rattus*). Indian Journal of Agricultural Research 77: 502–504.

Singla N, Kaur R 2014. Potential of citronella oil as rodent repellent measured as aversion to food. Applied Biological Research 16: 191–198.

Singla N, Thind RK, Mahal AK 2014. Potential of eucalyptus oil as repellent against house rat, *Rattus rattus*. The Scientific World Journal 2014: 249284. doi:10.1155/2014/249284.

Spurr EB 1993. Feeding by captive rare birds on baits used in poisoning operations for control of brushtail possums. New Zealand Journal of Ecology 17: 13–18.

Spurr E 2000. Impacts of possum control on non-target species. In: Montague TL ed. The brushtail possum: biology, impact and management of an introduced marsupial. Lincoln, Manaaki Whenua Press. Pp. 175–186.

Spurr EB 2008. Bird (kea) repellent research. Unpublished report prepared for Kea Conservation Trust. Available on request from the Kea Conservation Trust www.keaconservation.co.nz (accessed 10 August 2015).

Spurr EB, Porter RER 1998. Bird repellents for use on carrot baits for possum control. Lincoln, Manaaki Whenua Landcare Research. Abstract available online: http://www.tbfree.org.nz/ (accessed 10 August 2015).

Spurr EB, Porter RER, Thomson C 1995. Repellents to reduce risks to birds from brodifacoum used for poisoning rats. Part 1. Palatability of bird repellents to rats. Lincoln, Manaaki Whenua Landcare Research.

Spurr EB, Porter RER, Thomson C 2001. Palatability of bird repellents to *Rattus norvegicus*. Pest Management Science 57: 615–619.

Stanley MC, Lill A 2001. Response of silvereyes (*Zosterops lateralis*) to dietary tannins: the paradox of secondary metabolites in ripe fruit. Australian Journal of Zoology 49: 633–640.

Stone RJ 1979. Behavioural and physiological problems associated with the development of Curb. Bird Control Seminars Proceedings, Paper 14. http://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=1013&context=icwdmbirdcontrol. (accessed 10 August 2015).

Sweet D ed. 2012. Registry of toxic effects of chemical substances. Cincinnati, OH, US Department of Health and Human Services.

Swihart RK 1990. Quebracho, thiram, and methiocarb reduce consumption of apple twigs by meadow voles. Wildlife Society Bulletin 18: 162–166.

Tupper SK, Werner SJ, Carlson JC, Pettit SE, Wise JC, Lindell CA, Linz GM. 2014. European starling feeding activity on repellent treated crops and pellets. Crop Protection 63: 76–82.

Udy PB, Pracy LT 1981. Baits, birds and field operations. Counterpest 6: 13–15.

van Klink P, Crowell MD 2015. Kea (*Nestor notabilis*) survivorship through a 1080 operation using cereal baits containing the bird repellent d-pulegone at Otira, central Westland. DOC Research & Development Series No. 344. Wellington, Department of Conservation.

Veltman CJ, Westbrooke IM 2011. Forest bird mortality and baiting practices in New Zealand aerial 1080 operations from 1986 to 2009. New Zealand Journal of Ecology 35: 21–29.

Vishwanath JM, Desko AG, Riley AL 2011. Caffeine-induced taste aversions in Lewis and Fischer rat strains: differential sensitivity to the aversive effects of drugs. Pharmacology, Biochemistry and Behavior 100: 66–72.

Wager-Page SA, Mason JR 1996. Ortho-aminoacetophenone, a non-lethal repellent: the effect of volatile cues vs direct

contact on avoidance behaviour by rodents and birds. Pesticide Science 46: 55–60.
Wagner KK, Nolte DL 2001. Comparison of active ingredients and delivery systems in deer repellents. Wildlife Society Bulletin 29: 322–333.
Watkins RW, Gill EL, Bishop JD, Gurney JE, Scanlon CB, Heffernan M-L, Nadian AK, Feare CJ, Cowan DP 1994. Cinnamamide: a vertebrate repellent. Advances in the Biosciences 93: 473–478.
Watkins RW, Gill EL, Bishop JD 1995. Evaluation of cinnamamide as an avian repellent: determination of a dose-response curve. Pesticide Science 44: 335–340.
Watkins RW, Gurney JE, Cowan DP 1998. Taste-aversion conditioning of house mice (*Mus domesticus*) using the non-lethal repellent, cinnamamide. Applied Animal Behaviour Science 57: 171–177.
Watkins RW, Lumley JA, Gill EL, Bishop JD, Langton SD, MacNicoll AD, Price NR, Drew MGB 1999. Quantitative structure-activity relationships (QSAR) of cinnamic acid bird repellents. Journal of Chemical Ecology 25: 2825–2845.
Welch JF 1954. A review of chemical repellents for rodents. Journal of Agriculture and Food Chemistry 2: 142–149.
Werner SJ, Provenza FD 2011. Reconciling sensory cues and varied consequences of avian repellents. Physiology and Behavior 102: 158–163.
Werner SJ, Homan HJ, Avery ML, Linz GM, Tillman EA, Slowik AA, Byrd RW, Primus TM, Goodall MJ 2005. Evaluation of Bird Shield™ as a blackbird repellent in ripening rice and sunflower fields. Wildlife Society Bulletin 33: 251–257.
Werner SJ, Cummings JL, Tupper SK, Hurley JC, Stahl RS, Primus TM 2007. Caffeine formulation for avian repellency. Journal of Wildlife Management 71: 1676–1681.
Werner S, Tupper S, Linz G, Homan HJ 2009a. Evaluation and development of blackbird repellents for agricultural applications. National Sunflower Association Research Forum, Bismark, ND. 5 p.

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Werner SJ, Carlson JC, Tupper SK, Santer MM, Linz GM. 2009b. Threshold concentrations of an anthraquinone-based repellent for Canada geese, red-winged blackbirds, and ring-necked pheasants. Applied Animal Behaviour Science 121: 190–196.
Werner SJ, Linz GM, Tupper SK, Carlson JC 2010. Laboratory efficacy of chemical repellents for reducing blackbird damage in rice and sunflower crops. Journal of Wildlife Management 74: 1400–1404.
Werner SJ, DeLiberto ST, Pettit SE, Mangan AM 2014. Synergistic effect of an ultraviolet cue for an avian repellent and protection of agricultural crops. Applied Animal Behaviour Science 159: 107–113.
Werner SJ, DeLiberto ST, Mangan AM, Pettit SE, Ellis JW, Carlson JC 2015. Anthraquinone-based repellent for horned larks, great-tailed grackles, American crows and the protection of California's specialty crops. Crop Protection 72: 158–162.
White BC, Mason FD 1985. Caffeine-induced taste aversion and mimetic responses. Pharmacology, Biochemistry and Behavior 23: 515–518.
Wiggins NI, McArthur C, McLean S, Boyle R 2003. Effects of two plant secondary metabolites, cineole and gallic acid, on nightly feeding patterns of the common brushtail possums. Journal of Chemical Ecology 29: 1147–1464.
Willoughby IH, Junks RL, Morgan GW, Pepper H, Budd J, Mayle B 2011. The use of repellents to reduce predation of tree seed by wood mice (*Apodemus sylvaticus* L.) and grey squirrels (*Sciurus carolinensis* Gmelin). European Journal of Forest Research 130: 601–611.
Young WR, Zevallos DC 1960. Studies with chemical seed treatments as bird repellents for the protection of germinating maize in the Mexican tropics. FAO Plant Protection Bulletin 8: 37–42.
Zeinelabdin MH, Bullard RW, Jackson WB 1984. Mode of repellent activity of condensed tannin to quelea. Proceedings Bird Control Seminar Paper 272. Pp. 241–244.
Zungu MM, Downs CT 2015. Effects of tannins on fruit selection in three southern African frugivorous birds. Behavioural Processes 111: 84–89.
Zurcher NJ, Johnson RJ, Timm RM 1983. Methiocarb and thiram as corn seed repellents for thirteen-lined ground squirrels. Wildlife Society Bulletin 11: 38–42.