Potential invertebrate antifeedants for toxic baits used for vertebrate pest control

A literature review

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ABSTRACT

Baits used in New Zealand for the control of introduced vertebrate pests, such as brushtail possums and rats, are eaten by non-target invertebrates, such as ants, beetles and weta. Potential invertebrate antifeedants that could be added to the baits were identified by manual and computer-based searches of the scientific literature, and by consulting other scientists, scientific organisations, and chemical companies. A large number of compounds with invertebrate antifeedant activity (mainly repellents and deterrents) were identified. However, only a few invertebrate antifeedants have been developed for practical use. Most have been used as insect repellents for the protection of humans from biting insects (e.g. diethyl toluamide (DEET), dimethyl phthalate (DMP), citronella oil, and eucalyptus oil). A few invertebrate antifeedants have been used for the protection of seeds, crops, stored products, and other commodities (e.g. neem oil), and also to prevent invertebrates from eating baits used for vertebrate pest control (e.g. DMP and alpha-cypermethrin). We recommend that DEET, DMP, citronella oil, eucalyptus oil, neem oil, and alpha-cypermethrin be evaluated for palatability to possums and rats, and then for antifeedant effects to invertebrates likely to eat baits in New Zealand. Commercially available insect repellents (such as in aerosol fly sprays or slow-release polymer strips) should also be evaluated for use in bait stations to reduce invertebrate consumption of baits.

Keywords: Invertebrates, insect repellents, antifeedants, baits, vertebrate pest control

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1. Introduction

Baits containing toxicants such as sodium monofluoroacetate (1080) or brodifacoum are used extensively in New Zealand, both in bait stations and aerially spread over the ground, for the control of introduced vertebrate pests such as the brushtail possum (*Trichosurus vulpecula*), ship rat (*Rattus rattus*), Norway rat (*R. norvegicus*), kiore (*R. exulans*), and house mouse (*Mus musculus*). The baits used in bait stations are usually either cereal-based pellets or fruit-based pastes or gels, whereas those spread from the air are either cereal-based pellets or chopped carrots. As well as being eaten by the target species, these baits are also eaten by invertebrates (Sherley et al. 1999; Spurr & Drew 1999; Lloyd & McQueen 2000). In aerial operations, exposure of the toxicant to invertebrates is 'one-off' or infrequent, but on offshore islands and in some mainland situations pest control operators are committed to using baits in bait stations, sometimes for extended periods of time, which gives prolonged exposure of the toxicants to invertebrates. Neither aerial distribution of 1080 nor use of brodifacoum in bait stations is likely to have any deleterious long-term impacts on ground-dwelling invertebrate populations (Spurr 1994, 1996a, 2000; Sherley et al. 1999; Spurr & Drew 1999). However, concern has been expressed that invertebrates that eat baits may be transporting toxicants into the environment and, through the food chain, into insect-feeding birds such as the brown kiwi (*Apteryx australis*) and morepork (*Ninox novaeseelandiae*), and mammals such as the short-tailed bat (*Mystacina tuberculata*) (Eason et al. 1999, 2001, 2002; Innes & Barker 1999; Lloyd & McQueen 2000).

If invertebrates could be prevented from eating baits then they would not ingest toxicants and transport them through the food chain. The use of an invertebrate antifeedant that is palatable to possums and rodents would achieve this. This paper reviews the international literature on invertebrate antifeedants, as a basis for selecting the most promising to test for (a) palatability to possums and rodents and (b) antifeedant effects on those New Zealand invertebrates considered likely to feed on baits used for vertebrate pest control.

2. Methods

The international scientific literature on invertebrate antifeedants was searched manually and by using computer-based abstracting services (CAB Abstracts, Current Contents, and Agricola). The following scientists in New Zealand and other countries, scientific organisations, and chemical companies were also consulted: E. Burgess and B. Philip (HortResearch, New Zealand); J. Berry, D. Morgan and R. Harris (Landcare Research, New Zealand); L. Clark (National Wildlife Research Center, USA); T. Day (AgResearch, New Zealand); T. Krause (Wyoming, USA); L. Roy (Alberta Research Council, Canada); R. Watkins (Central Science Laboratory, UK); D. Whisson (University of California, Davis, USA); S. Wratten (Lincoln University, New Zealand); BASF-New Zealand (Christchurch); Bayer (NZ) Ltd (Christchurch); Elliott Chemicals (Auckland, New Zealand); Essential Oils of New Zealand (Rangiora); Flybusters Insect Control (NZ) Ltd (Auckland); Kiwicare (Christchurch, New Zealand); and Suntec (NZ) Ltd (Tokomaru). For the computer-based searches we used combinations of the terms 'invertebrate', 'arthropod', 'insect', 'antifeedant', 'inhibitor', 'repellent', 'suppressant', and 'deterrent' (see Appendix 1).

The terms 'antifeedant', 'inhibitor', 'repellent', 'suppressant', and 'deterrent' are often used interchangeably in the literature, but have different meanings. Repellents actively repel the invertebrate away from the source of the repellent before it has made contact with it. Suppressants suppress the initiation of feeding after the invertebrate has made contact with the source. Deterrents deter the continuation of feeding after feeding has started (Chapman 1974; Schoonhoven 1982; Warthen & Morgan 1990). The terms 'antifeedant' or 'inhibitor' may be used when it is not possible to determine the mode of action of a compound. We have used the term 'antifeedant' in this review unless the specific action of a compound is known. Antifeedants inhibit feeding without killing the invertebrate.

The terms 'invertebrate', 'arthropod', and 'insect' are all used in the literature in reference to antifeedants. Invertebrate refers to all animals without a backbone. Arthropod refers to invertebrates with a hard, jointed exoskeleton (Phylum Arthropoda). This includes isopods (Class Crustacea), spiders, harvestmen, mites, and ticks (Arachnida), millipedes (Diplopoda), springtails (Collembola), and insects (Insecta). However, arthropods do not include invertebrates such as earthworms (Phylum Annelida) or slugs and snails (Mollusca), which have also been recorded eating baits used for possum or rodent control.

More than 1000 references on invertebrate antifeedants were retrieved. CAB Abstracts (January 1990 to January 2001) had no references listed under the search term 'invertebrate antifeedant', but 172 references under 'insect antifeedant' and 724 under 'insect repellent' (Appendix 1). There were 5224 references under 'insect' and 'repellent' combined, including some relevant references not listed using the phrase 'insect repellent'. Some irrelevant references were also obtained. Included in the references retrieved (and references cited within) were a number of reviews of invertebrate antifeedants (e.g. Chapman 1974; Vigneron 1978; Ascher 1979, 1987, 1992; Bernays 1983; Szentesi & Jermy 1985; Norris 1986, 1990; Russell 1986; Brud & Gora 1990; Curtis et al. 1990; Jermy 1990; Schmutterer 1990; Warthen & Morgan 1990; Ahmad et al. 1993; Jain & Tripathi 1993; Mordue & Blackwell 1993; Nigam et al. 1994; Qui et al. 1998; Mulla & Su 1999; Srivastava et al. 1999). Information from these reviews forms the basis of the present review.

3. Results

3.1 OVERVIEW

Many compounds with invertebrate antifeedant activity (mainly repellents and deterrents) have been identified. For example, Norris (1990) listed 435 natural insect repellents and Warthen & Morgan (1990) listed 549 natural insect feeding deterrents. New antifeedants continue to be discovered (e.g. see Gerard et al. 1993; Russell & Lane 1993; Yap et al. 1998; Srivastava et al. 1999). The literature on invertebrate antifeedants can be divided into two groups: literature on compounds used to protect humans from biting / piercing / sucking invertebrates such as mosquitoes (Order Diptera) and sandflies (Diptera), and literature on compounds used to protect seeds, crops, stored products, and commodities such as woollen clothes and carpets from chewing / boring invertebrates such as cockroaches (Blattodea), locusts (Orthoptera), aphids (Hemiptera), beetles (Coleoptera), weevils (Coleoptera), moth larvae (Lepidoptera), and ants (Hymenoptera). Compounds in the former group are repellents, whereas those in the latter group are usually either suppressants or deterrents. The same compounds are seldom used for both purposes. A further division occurs between natural and synthetic compounds. Natural compounds are generally regarded as more acceptable for pest control purposes than synthetic ones (Jermy 1983).

Investigations into antifeedants have been carried out almost exclusively in the laboratory, usually with only one invertebrate species, using short-term, often two-choice tests, on a variety of substrates, and without behavioural observations (Bernays 1983; Jermy 1990). Most experiments have used larvae of the lepidopterans *Spodoptera* spp. (armyworms), *Heliothis* spp. (budworms, earworms), and *Pieris* spp. (cabbage white butterflies), or the locusts *Locusta migratoria* and *Schistocerca gregaria*. These are all insects that can be reared in laboratories (Jermy 1990; Warthen & Morgan 1990). Short-term tests such as these ignore the possibility of habituation, and morphogenetic or other toxic effects. The variety of substrates (carriers for the test compound, e.g. food, agar, filter paper) used in the tests may also have influenced the insect's response to a chemical (Jermy 1990). Furthermore, many of the compounds tested are not available or not available in suitable quantities for further studies (Jermy 1990; Russell & Lane 1993). It is therefore difficult to judge what proportion of the numerous antifeedants described so far can be regarded as promising for practical purposes (Jermy 1990).

To date, only a few of the large number of potential invertebrate antifeedants identified have been developed for practical use. Most are insect repellents for the protection of humans from biting insects. Before about 1940, four insect repellents were commercially available: citronella oil, dimethyl phthalate (DMP), indalone (butyl 3,4-dihydro-2,2-dimethyl-4-oxo-2H-pyran-6-carboxylate), and Rutgers 612 (2-ethyl-1,3-hexanediol) (Brown & Herbert 1997). Since World War 2, the most widely used, and most effective, insect repellent has been diethyl toluamide (DEET) (Brown & Herbert 1997; Chou et al. 1997; Qui et al. 1998). Other potential insect repellents have been tested, and some, such as N,N-diethyl-2-phenylacetamide (DEPA), have been found to be as effective as DEET (Kalyanasundaram et al. 1994). However, they have not yet been commercially developed.

A few invertebrate antifeedants have been developed for the protection of seeds, crops, stored produce, and other commodities. In India, for example, various invertebrate-antifeedant extracts of neem (*Azadirachta indica*) have been used to protect crops and stored grain for many years (Mordue & Blackwell 1993; Nigam et al.1994). In the UK, polygodial, an extract from the water-pepper plant (*Polygonum hydropiper*), has been used experimentally to protect barley from aphids (Warthen & Morgan 1990; Jain & Tripathi 1993; Pickett et al. 1997; Srivastava et al. 1999), but polygodial is not available commercially. In New Zealand, most products used for the control of invertebrate pests in these situations are organophosphate or carbamate insecticides (O'Connor 2000). For example, seeds are treated with organophosphates such as maldison, carbamates such as furathiocarb and methiocarb, or the nitromethylene imidacloprid, and stored grain is treated with organophosphates such as dichlorvos, maldison, and pirimiphos-methyl, or carbamates such as propoxur (O'Connor 2000). These products are primarily insecticidal but some may also have a repellent or deterrent function. Invertebrate antifeedants have been identified for the protection of seeds (e.g. Blank et al. 1986; Watkins 1996; Watkins et al. 1996), seedlings (e.g. Barratt et al. 1993), growing crops (e.g. Barrington et al. 1993; Russell & Lane 1993), and commodities such as woollen clothes and carpets (e.g. Gerard & Ruf 1991; Gerard et al. 1993). However, these have yet to be commercially developed.

Invertebrate antifeedants have also been used to reduce the incidence of invertebrates eating baits used for vertebrate pest control. A synthetic pyrethroid (probably alpha-cypermethrin) is incorporated in Storm® (American Cyanamid Co.), a bait used for rat control and containing the anticoagulant flocoumafen, to prevent attack by insects (according to a product information brochure). Chemical insect repellents have also been added to bait used in traps for small mammals in the USA, to reduce insect removal of the baits. Coleman (1950) and Golley (1961) mixed DDT into baits (peanut butter and grain), and Anderson & Ohmart (1977) mixed DMP into baits (peanut butter and rolled oats). The DMP-treated baits repelled ants for 20 hours and still attracted rodents in about the same numbers and proportions as untreated baits. However, the rodents were not required to eat these baits, because they were used only as lures, so the palatability of DMP to rodents was not determined. The use of DMP as an insect repellent in baits for small mammals was also investigated in an unsighted MSc thesis (Roese 1984).

Bait removal by insects has also been reduced by applying a chemical insect repellent to an area around traps, rather than by mixing it into the baits. Chabreck et al. (1986) applied diazinon and Dursban® (containing chlorpyrifos) to trap sites. Gettinger (1990) sprayed Raid Ant & Roach Killer® (containing 0.95% propoxur and 83% petroleum distillate) around trap sites. All treatments reduced bait removal by insects such as ants. However, as above, the rodents were not required to ingest the insect repellents.

Honeybee (*Apis mellifera*) removal of apple paste bait containing 1080 used for brushtail possum control in New Zealand was reduced experimentally by the addition of molasses or oxalic acid (Goodwin & Ten Houten 1991). Possums readily ate the baits containing molasses but not the baits containing oxalic acid (Morgan et al. 1993). However, molasses turned the apple paste black, and the Pesticides (Vertebrate Pest Control) Regulations 1983 require baits containing

1080 to be a specific shade of green. Morgan et al. (1993) screened a further 29 compounds for repellency to honeybees. Of the eight compounds most repellent to honeybees, three (0.5–1% isovaleric acid, 0.5% N,N-dibutylformamide, and 1% maleic anhydride) did not reduce the palatability of apple paste to possums. The other five (0.5% Ambush® 50 EC (containing 5% permethrin), 1% safrole, 0.5% salicyaldehyde, 0.5% carvacrol, and 0.5% 2-heptanone) did reduce palatability to possums. Isovaleric acid was the most cost-effective, but proved too unpleasant for field staff to use (D.R. Morgan pers. comm.). Spurr (1996b) found that 1% isovaleric acid, 1% valeric acid, 1% N,N-dibutylformamide, 1% maleic anhydride, and 1% 2-heptanone in sugar syrup were repellent to German and common wasps (*Vespula germanica* and *V. vulgaris*).

Cinnamon oil is currently added to baits containing 1080 used for possum control (0.1% w/w) to mask the smell and taste of 1080 to possums (Morgan 1990). However, it is also an invertebrate antifeedant. For example, it reduced the incidence of invertebrates, predominantly ants, beetles, and weta (Orthoptera), feeding on baits by more than 50% (Spurr & Drew 1999). It also repels German and common wasps (E.B. Spurr pers. obs).

The most potent invertebrate feeding deterrents known are warburganal, muzigadial, and azadirachtin (Warthen & Morgan 1990). Warburganal and muzigadial are active at 0.1 ppm against armyworms (*Spodoptera* spp.), and azadirachtin is active on a host of different invertebrates, at concentrations as low as 0.35 ppm against the fall armyworm (*Spodoptera frugiperda*) (Warthen & Morgan 1990). Ugandensidial and polygodial are also active against armyworms at 0.1 ppm; aristolochic acid is active against locusts (*Locusta migratoria*) at 0.01 ppm, pilocarpine is active against the silkworm (*Bombyx mori*) at 0.04 ppm, salicin is active against *B. mori* at 0.06 ppm, and strychnine is active against *B. mori* at 0.03 ppm (Warthen & Morgan 1990). There has been no direct comparison of the effectiveness of DEET, claimed to be the most potent insect repellent developed so far (Brown & Herbert 1997; Chou et al. 1997; Qui et al. 1998), and azadirachtin, muzigadial, and warburganal, claimed to be the most potent invertebrate feeding deterrents known (Warthen & Morgan 1990).

It is extremely difficult to compare the potency of different antifeedants on different invertebrate species, because some antifeedants that are potent on certain invertebrate species have no effect on other invertebrate species (Warthen & Morgan 1990; Pickett et al. 1997). For example, polygodial, effective against aphids, has little antifeedant effect on beetles (Pickett et al. 1997). On the other hand, ajugarins (in the clerodane class of diterpenoids) are extremely effective against beetles, particularly those in the family Chrysomelidae, but not against aphids (Pickett et al. 1997).

3.2 DESIRABLE CHARACTERISTICS OF ANTIFEEDANTS FOR USE IN BAITS

Not all invertebrate antifeedants possess the qualities required for economic and practical use (Chapman 1974). Ascher (1992) listed 16 desired properties of an invertebrate antifeedant:

1. No phytotoxicity
2. Low toxicity to non-target animals
3. Broad-spectrum antifeedant efficacy against pests
4. Otherwise toxic against pests
5. Active at very low concentrations
6. Persistence
7. Systemic and translaminar action
8. No effect on taste, smell and appearance of product
9. No toxic or taste-deteriorating metabolites
10. Easy application
11. Easy formulation
12. Storage stability
13. Low cost, steady supply
14. High concentration in source plant
15. Compatible with other forms of insect pest management
16. No habituation or resistance.

Only (1) 'no phytotoxicity', (4) 'otherwise toxic against pests', (7) 'systemic and translaminar action', and (14) 'high concentration in source plant' do not apply to the requirements for an invertebrate antifeedant in baits for vertebrate pest control, as we want to protect native invertebrates, not destroy them. However, this does not necessarily exclude the use of an insecticide because many insecticides have repellent and / or deterrent properties (e.g. Thomson 1982; Husain et al. 1994; Nigam et al. 1994; O'Connor 2000). Thus, an insecticide may be appropriate as an antifeedant if it clearly prevents invertebrates from eating the bait to which it is applied.

Other criteria required or preferred for an invertebrate antifeedant for baits include:

17. Low toxicity to invertebrates
18. Palatable to possums and rats
19. Able to withstand heating to 65–90°C
20. Already registered in New Zealand (with the Agricultural Compounds and Veterinary Medicines group, Ministry of Agriculture and Forestry), or overseas (e.g. with the US Environmental Protection Agency), or does not require registration.

Very few potential invertebrate antifeedants have been tested for palatability to possums and rats. Morgan (1990) found that 20 out of 39 food flavours tested (most presented at a concentration of 0.01% vol/wt on barley) did not reduce the palatability of the barley to possums. Of these, only cinnamon oil is likely to be antifeedant to invertebrates. Very low concentrations of flavours such as blackberry and strawberry did reduce the palatability of barley to possums. Cinnamamide, a known invertebrate antifeedant, is palatable to possums but not to Norway rats (Crocker et al. 1993; Spurr & Porter 1998) or house mice (Gurney et al. 1996).

An ability to withstand temperatures of 65–90°C is required because these temperatures are encountered in the process of manufacturing the cereal-based baits used for possum and rodent control (W. Simmons, Animal Control Products, pers. comm.).

Compounds already registered in New Zealand or overseas for other purposes (e.g. as insecticides) would be easier and less costly to register as invertebrate antifeedants in baits used for vertebrate pest control than compounds not already registered.

3.3 POTENTIAL INVERTEBRATE ANTIFEEDANTS, IN ALPHABETICAL ORDER

This section provides information on some compounds identified in the literature as insect repellents or deterrents. Information about these compounds given above is repeated below for completeness. Some of the compounds are clearly not suitable for use as invertebrate antifeedants in baits used for vertebrate pest control, but they have been included below so that they can be discounted from further consideration.

1. Alpha-cypermethrin

Description

Alpha-cypermethrin is a synthetic pyrethroid, with insecticidal and antifeedant activity. Technical-grade alpha-cypermethrin is a white powder (> 90% pure). It has a weak aromatic odour, is relatively stable to light, and is thermally stable up to 220°C (Tomlin 1994). Commercially available formulations (emulsifiable concentrates, suspension concentrates, and wettable powders) contain 1.5–35% alpha-cypermethrin.

Invertebrate activity

Alpha-cypermethrin was repellent to the mites *Tetranychus urticae* and *Panonychus ulmi* (Ahn et al. 1993), the German cockroach (*Blattella germanica*) (Fuchs 1988), honeybee (de Wael & van Laere 1989), and armyworm (Fisk & Wright 1992). A concentration of 0.2% alpha-cypermethrin in a gel bait was repellent to (unspecified) cockroaches (Terekhova 1995).

Alpha-cypermethrin is believed to be the synthetic pyrethroid incorporated into Storm® (American Cyanamid Co.), a bait used for rat control containing the anticoagulant flocoumafen, to prevent attack by insects. The concentration of alpha-cypermethrin in the bait is unknown but, because it is not listed, is presumably < 0.05%. Its effectiveness at deterring invertebrates is also unknown.

Vertebrate activity

The acute oral LD_{50} of alpha-cypermethrin to Norway rats is 474 mg/kg (Tomlin 1994). In 90-day feeding trials, rats receiving 60 mg/kg (0.006%) alpha-cypermethrin in their diet suffered no ill effects (Tomlin 1994). Storm® rat bait, containing a synthetic pyrethroid believed to be < 0.05% alpha-cypermethrin, is readily eaten by both rats and mice. The palatability of alpha-cypermethrin to possums is unknown.

Availability

Alpha-cypermethrin-based products (emulsifiable concentrates, suspension concentrates, and wettable powders) are readily available from chemical suppliers. Technical-grade alpha-cypermethrin is not readily available.

2. Camphor

Description

Camphor is a natural compound derived from the camphor tree (*Cinnamomum camphora*). It has a familiar and penetrating odour, and a slightly bitter and cooling taste. Its boiling point is 204°C, but it sublimes appreciably at room temperature and pressure (Budavari 1996).

Invertebrate activity

Camphor was commonly used as a moth repellent (Budavari 1996). It is a feeding deterrent for the tobacco budworm (*Heliothis virescens*) (Lepidoptera) and the boll weevil (*Anthonomus grandis*) (Coleoptera) (Miles et al. 1985), and a repellent to four species of stored-products beetles (*Sitophilus granarius*, *S. zeamais*, *Trilobium castaneum*, *Prostephanus truncatus*) (Obeng et al. 1998).

Vertebrate activity

The palatability of camphor to possums and rodents is unknown.

Availability

Camphor is readily available (e.g. from Sigma Chemical Co.).

3. Capsaicin

Description

Capsaicin is one of the active ingredients in the fruit of chillis and peppers (*Capsicum* spp.). It has a pungent odour, and burning taste (Budavari 1996).

Invertebrate activity

Capsaicin has been shown to have antifeedancy to various invertebrates (Warthen & Morgan 1990). For example, capsaicin from capsicum in an oleoresin has been used against cotton pests (Mayeux 1996). Extracts of capsicum were also repellent to one species of stored-products beetle (*Sitophilus zeamais*), although not so much to another (*Tribolium castaneum*) (Ho et al. 1997). Nougard (Environmental Health Products, Auckland), containing the active ingredient capsaicin, is available in New Zealand as an invertebrate and vertebrate repellent for protection of buildings, citrus trees, and nursery stock.

Vertebrate activity

Capsaicin is considered universally repellent to mammals at concentrations between 10 and 100 ppm (Mason 1988). It is repellent to Norway rats at concentrations as low as 1% (Mason et al. 1991).

Availability

Capsaicin is readily available.

4. Cinnamamide

Description

Cinnamamide is a derivative of cinnamic acid.

Invertebrate activity

Cinnamamide, at concentrations of ≤ 5%, is an antifeedant for a variety of invertebrates, including the field slug (*Deroceras reticulatum*), adult grain weevil (*Sitophilus granarius*), vine weevil (*Otiorhynchus sulcatus*), cereal aphid (*Sitibion avenae*), larval tomato moth (*Lacanobia oleracea*), and large cabbage white butterfly (*Pieris brassicae*) (Watkins 1996; Watkins et al. 1996).

Vertebrate activity

Cinnamamide is not repellent to possums at a concentration of 0.5% on carrot bait (Spurr & Porter 1998). However, it is repellent to rodents, including Norway rats, at a concentration of 0.25–0.5%, (Crocker et al. 1993; Spurr & Porter 1998) and house mice, at a concentration of 0.1% (Gurney et al. 1996).

Availability

Cinnamamide is readily available.

5. Cinnamon oil

Description

Cinnamon oil is derived from *Cinnamomum* species. Its chief component is cinnamaldehyde (up to 90%), a yellowish oil liquid, with a strong cinnamon odour (Budavari 1996). It also contains cinnamic acid. The boiling point of cinnamaldehyde is 246°C, and of cinnamic acid is 300°C (Budavari 1996).

Invertebrate activity

Cinnamon oil, at 0.5% concentration, reduced numbers of the beetle *Zabrotes subfasciatus* feeding on bean seeds by 96% (Oliveira & Vendramim 1999). Extracts of cinnamon were also highly repellent to the stored-products beetles *Tribolium castaneum* and *Sitophilus zeamais* (Ho et al. 1997; Huang & Ho 1998). Cinnamite, a synthesised analogue of cinnamon oil, is effective at concentrations of 0.20–0.25% against mites, aphids, and thrips (Thysanoptera) in greenhouses (Parrella et al. 1999).

Cinnamon oil, at 0.1% w/w, reduced the incidence of invertebrates, predominantly ants, weta (Orthoptera), and beetles, feeding on baits (carrot and cereal-based) by more than 50% for at least 3 days (Spurr & Drew 1999). Cinnamon oil (0.1%) is also repellent to German and common wasps (Hymenoptera) (E.B. Spurr pers. obs).

Cinnamon oil is currently added to baits used for possum control (at 0.1–0.15% w/w), to mask the smell and taste of 1080 to possums (Morgan 1990; W. Simmons, ACP, pers. comm.) but not to baits for rat control (because it is not needed to mask brodifacoum). Because of the rapid loss of cinnamon oil from baits, it has been recommended recently that the cinnamon oil concentration be increased to 0.3% (D.R. Morgan pers. comm.).

Vertebrate activity

Above 0.5%, cinnamon oil reduced the palatability of baits to possums. Cinnamon oil (0.3% w/w) reduced the palatability of a paste bait to laboratory rats (L. Milne pers. comm.).

Availability

Cinnamon oil is available from Bush Boake Allen (Auckland) for c. NZ$100/litre, and from Sigma Chemical Co. for A$128.10/100 ml (Sigma 2000).

6. Citronella oil

Description

Citronella oil is commonly extracted from citronella grass (*Cymbopogon nardus*), lemongrass (*C. citratus*), and related species (e.g. *C. winterianus*). The main component of citronella oil is citronellal, and it also contains citronellol. Citronellol has a boiling point of 224.5°C (Budavari 1996).

Invertebrate activity

Citronella oil was the most popular insect repellent for human use before 1940 (Brown & Herbert 1997), and is still used in some present-day insect repellents (e.g. Brown & Herbert 1997; Chou et al. 1997). It was not as effective as DEET in laboratory tests (Chou et al. 1997; Cockcroft et al. 1998; Thorsell et al. 1998), but was just as effective in a field test (Thorsell et al. 1998). When applied to human skin, citronella oil (0.05–10%) was reported as being effective against biting insects for 4 hours or even overnight (Brown & Herbert 1997). A 10% solution was effective in the field for at least 8 hours (Thorsell et al. 1998). When applied to clothing, citronella oil was effective against the human body louse (*Pediculus humanus*) for at least 29 days (Mumcuoglu et al. 1996). Product trade names include Natrapel (Brown & Herbert 1997) and Buzz Away, which also contains eucalyptus oil (Chou et al. 1997). Citronella oil is also available in candles (at a concentration of 3–5%) to reduce the incidence of biting insects (Lindsay et al. 1996). Citronella oil is toxic to beetles when there is direct contact of the insect with the oil (Lale 1991).

When added to sugar syrup (at 0.5–1%), citronella oil reduced the number of Indian honeybees (*Apis cerana indica*) collecting syrup for 30 hours (Patyal & Kumar 1989). In this regard, citronella oil was more effective than eucalyptus oil (Patyal & Kumar 1989).

Vertebrate activity

The palatability of citronella oil to possums and rodents is unknown.

Availability

Citronella oil is readily available, and may be obtained from Bush Boake Allen (Auckland) for NZ$57.48/kg + GST, and from Essential Oils of New Zealand Ltd for NZ$100/litre + GST. Citronellal (3,7-dimethyl-6-octenal) is obtainable from Sigma Chemical Co. for A$22.80/100 ml (Sigma 2000).

7. Cypermethrin

Description

Cypermethrin is a synthetic pyrethroid, with insecticidal and antifeedant activity. It is a yellow-brown viscous semi-solid at ambient temperatures, odourless, relatively stable to light, and thermally stable up to 220°C (Tomlin 1994).

Invertebrate activity

Cypermethrin reduced food consumption in the bulb mite (*Rhizoglyphus robini*) (Cohen & Joseph 1992), mustard beetle (*Phaedon cochleariae*) (Hajjar & Ford 1990), German cockroach (Ross & Cochran 1992), and armyworm (Fisk & Wright 1992). The concentration of cypermethrin in the mustard beetle study was 0.05%. However, in another study, 1–5 µl of cypermethrin did not deter cockroaches from eating a gel bait (Robinson et al. 1999). Cypermethrin was highly repellent, and more repellent than permethrin, chlorpyrifos, diazinon, bendiocarb, or propoxur, to Argentine ants (*Linepithema humile* = *Iridomyrmex humilis*) (Knight & Rust 1990). A 0.01% cypermethrin spray reduced visits by Indian honeybees (*Apis cerana indica*) to radish crops for up to 9 days (Rathore et al. 1987). In a laboratory trial, cypermethrin was not as repellent to mosquitoes as DEET, but another pyrethroid (Pyrethroid-T, containing the alpha-cyano, 3-phenoxybenzyl moiety) was more repellent than DEET (Braverman & Chizov-Ginzburg 1997).

Vertebrate activity

The acute oral LD_{50} of cypermethrin to Norway rats is 7180 mg/kg (Tomlin 1994). Its palatability to possums and rodents is unknown.

Availability

Products containing cypermethrin are readily available.

8. Diethyl toluamide (N,N-diethyl-3-methylbenzamide)

Description

Diethyl toluamide (DET or DEET), a synthetic compound, is a colourless to amber liquid, with a boiling point of 111°C (Tomlin 1994). It can also be obtained in powder form.

Invertebrate activity

DEET was first marketed as an insect repellent in the 1950s, and is now the most widely used and most effective commercially marketed repellent for biting insects in the world (Brown & Herbert 1997; Chou et al. 1997; Qui et al. 1998). Commercial products (e.g. Repel®) most commonly contain 20–30% DEET, but may contain 6–100% DEET.

DEET is effective against a wide range of biting and piercing/sucking insects, including mosquitoes, flies, mites (chiggers), ticks, and fleas (Siphonaptera). It can be applied to the skin, or to clothing, bedrolls, tents, and insect screens (Curtis et al. 1990; Qui et al. 1998). This implies that it actively repels invertebrates. Brown & Herbert (1997) claimed that DEET does not camouflage attractants emanating from the skin, but repels insects when they approach the skin to which it is applied. However, Dogan et al. (1999) claimed that the repellent action of DEET does not result from its physical properties, but from an inhibition of lactic acid, a component of human sweat, that is an attractant for mosquitoes. If this were the case, then DEET would not be an effective repellent in baits. This needs to be clarified.

The protection time of DEET when applied to skin is 1–6 hours (Curtis et al. 1990). To be effective for longer, it needs repeated application. Recently, encapsulation in polymers, gels, microcapsules, and microparticles has extended the protection time of DEET to 12–48 hours, or longer in some cases (Rutledge et al. 1996; Brown & Herbert 1997; Qui et al. 1998; Golenda et al. 1999; Salafsky et al. 1999). Incorporation into a bait may also extend the time for which it is effective.

No references were found to DEET being used as an antifeedant for invertebrate pests of stored grain.

DEET has insecticidal activity on contact, and has caused mortality of invertebrates such as larval mites (*Leptotrombidium fletcheri*) (e.g. Ho & Fauziah 1993).

Vertebrate activity

The acute oral LD_{50} of DEET to Norway rats is c. 2000 mg/kg (Tomlin 1994). The palatability of DEET to possums and rodents is unknown. However, in 200-day feeding trials, rats receiving 10 000 mg/kg diet suffered no ill-effects (Tomlin 1994).

Availability

DEET is readily available, and may be obtained from Global Science & Technology for NZ$163.50/litre.

9. Dimethyl phthalate (or diemthyl 1,2-benzenedicarboxylate)

Description

Dimethyl phthalate (DMP) is a colourless, oily liquid, with a slight aromatic odour, and a boiling point of 283.7°C (Tomlin 1994; Budavari 1996). It used to be available in powder form.

Invertebrate activity

DMP was one of the earliest synthetic insect repellents discovered (Brown & Herbert 1997). It is effective against a variety of invertebrates, including mosquitoes, sandflies, ticks, and mites (Frances 1994; Kalyanasundaram et al. 1994; Brown & Herbert 1997). It is not as effective as DEET (Curtis et al. 1990; Kalyanasundaram et al. 1994; Kumar et al. 1995; Brown & Herbert 1997) and, consequently, is not often used in present-day insect repellents. A commercial product (Dimp, Sterling Pharmaceuticals (N.Z.), Auckland), containing 31.7% DMP, claimed protection from insect bites for 3–4 hours.

DMP has been used as an invertebrate antifeedant in baits used for trapping small mammals. Peanut butter and rolled oat baits containing 4% DMP repelled ants for about 20 hours and still attracted rodents (*Peromyscus eremicus*, *Perognathus penicillatus*, and *Neotoma albigula*) in about the same numbers and proportions as untreated bait (Anderson & Ohmart 1977). A sugar syrup bait containing 2% DMP was not repellent to honeybees (Morgan et al. 1993).

Vertebrate activity

The acute oral LD_{50} of DMP to Norway rats is 8200 mg/kg (Tomlin 1994). The palatability of DMP to possums and rodents is unknown. However, in 2-year feeding trials, rats receiving 20 000 mg/kg diet suffered no ill effects (Tomlin 1994). A concentration of 4% DMP did not deter rodents from entering traps (Anderson & Ohmart 1977), but the palatability of DMP to these rodents was not known because they did not have to eat the baits.

Availability

DMP is readily available, and may be obtained from Global Science & Technology for NZ$116.50/litre.

10. Eucalyptus oil

Description

Eucalyptus oil is an essential oil of *Eucalyptus* species. Its chief constituent is eucalyptol (cineole), a colourless liquid, with a camphor-like odour, and spicy, cooling taste (Budavari 1996). The active ingredients have been described as eucamalol (Satoh et al. 1995), p-methane-3,8-diol (Trigg 1996a, 1996b; Trigg & Hill 1996), or pinene, cymene, and eucalyptol (Lin 1998). The major component of eucalyptus oil is usually eucalyptol if the yield is moderate to high, or pinene if it is low (Boland & Brophy 1993; Thorsell et al. 1998). The boiling point of eucalyptol is 176–177°C, and α-pinene is 155–156°C (Budavari 1996).

Invertebrate activity

Eucalyptus oil has been used as an invertebrate antifeedant, mainly as a repellent against biting insects (Watanabe et al. 1993; Trigg 1996a, 1996b; Trigg & Hill 1996; Chou et al. 1997; Thorsell et al. 1998). The effectiveness of eucalyptus oil may vary with the species from which it is derived, although the results may be conflicting. For example, Yan & Tan (1998) found that oil from *E. citriodora* was more effective than that from *E. globulus* against sawyers (Coleoptera: Cerambycidae), whereas Lin (1998) found that oil from *E. globulus* was more effective than that from *E. citriodora* against termites. Trade names of products containing eucalyptus oil include Mosiguard Natural, which contains 50% eucalyptus oil (Trigg 1996a, 1996b; Trigg & Hill 1996), and Buzz Away, which also contains citronella (Chou et al. 1997).

In some cases, eucalyptus-based repellents were as effective as DEET (Satoh et al. 1995; Trigg 1996a, 1996b; Thorsell et al. 1998) and in other cases not as effective (Collins et al. 1993; Mumcuoglu et al. 1996; Chou 1997). When used on humans as an insect repellent, eucalyptus-based products gave protection from biting invertebrates for about 8 hours (Trigg 1996a, 1996b; Trigg & Hill 1996; Thorsell et al. 1998). When applied to clothing, the repellency was extended to at least 8 days (Mumcuoglu et al. 1996). Solvent extracts of dried leaves may have longer repellency than the essential oil (Khan & Shahjahan 1998).

When added to sugar syrup, 1% eucalyptus oil reduced the number of Indian honeybees (*Apis cerana indica*) collecting syrup for only 6 hours, compared with 30 hours for 1% citronella oil (Patayal & Kumar 1989). When applied to host plants, 10% *E. citriodora* oil repelled three species of sawyers for 4–12 days, and 0.6% repelled them for 1–11 days (Yan & Tan 1998). A concentration of 2% eucalyptus oil on filter paper and wood flour repelled termites, but concentrations of less than 0.25% had virtually no termite repellency (Lin 1998). Sugar syrup containing 2% α-pinene, a component of eucalyptus oil, was not repellent to honeybees (Morgan et al. 1993).

Vertebrate activity

The palatability of eucalyptus oil to possums and rodents is unknown. However, possums eat eucalyptus leaves containing eucalyptus oil.

Availability

Eucalyptus oil is readily available, and may be obtained from Bush Boake Allen for NZ$42.02/kg + GST, and from Essential Oils of New Zealand for $100/litre + GST. Eucalyptol (cineole) is obtainable from Sigma Chemical Company for A$36.00/100 ml (Sigma 2000).

11. Muzigadial

Description

Muzigadial, like ugandensidial and warburganal, is a sesquiterpene derived from *Warburgia* species (Warthen & Morgan 1990).

Invertebrate activity

Muzigadial is one of the most potent invertebrate antifeedants identified, being active at 0.1 ppm on *Spodoptera* species (Warthen & Morgan 1990). In New Zealand, 9-deoxymuzigadial showed antifeedant and insecticidal activity against the webbing clothes moth (*Tineola bisselliella*), and antifeedant activity against the Australian carpet beetle (*Anthrenocerus australis*) at a concentration as low as 0.04% wool weight (Gerard et al. 1992).

Vertebrate activity

The palatability of muzigadial to possums and rodents is unknown.

Availability

Muzigadial has not been commercialised and is not readily available.

12. Neem oil

Description

Neem oil is derived from the seeds and leaves of the Indian neem tree (*Azadirachta indica*) and other species of the family Meliaceae. The major component of neem oil is azadirachtin. It also contains several other compounds, including azadiradion, isovepaol, meliantriol, nimbidin, salannin, and vepaol (Nigam et al. 1994; Mulla & Su 1999). It is a yellow oil, with a garlic odour, and bitter taste (Budavari 1996). Azadirachtin powder has a melting point of 154–158°C.

Invertebrate activity

Azadirachtin, a complex triterpenoid, is the most active antifeedant compound in neem oil, achieving 100% antifeedancy in some cases (Jain & Tripathi 1993; Mordue & Blackwell 1993; Nigam et al. 1994). The antifeedant activity of azadirachtin varies with extracts from different geographic regions and ecological conditions (Jermy 1990; Mulla & Su 1999). When feeding does occur, azadirachtin may have insecticidal properties (Mordue & Blackwell 1993; Mulla & Su 1999). Several other neem compounds (e.g. nimbin and azadirone) also show strong antifeedant activity, comparable to that of azadirachtin, but with virtually no toxicity (Aerts & Mordue 1997). Neem extracts were slightly more active than pure azadirachtin at equivalent azadirachtin concentrations, indicating that azadirachtin is not the only active ingredient in neem (Xie et al. 1995).

Neem derivatives have antifeedant and insecticidal activity against a wide range of invertebrates, including more than 220 species of insects belonging to the orders Isoptera, Orthoptera, Heteroptera, Homoptera, Coleoptera, Diptera, Lepidoptera, and Hymenoptera, and several species of mites (Warthen & Morgan 1990; Nigam et al. 1994; Xie et al. 1995; Richter et al. 1997; Mulla & Su 1999). Lepidoptera are extremely sensitive to azadirachtin and show effective antifeedancy from < 1 to 50 ppm. Coleoptera, Hemiptera, and Homoptera are less sensitive, with up to 100% antifeedancy being achieved at 100–600 ppm, whereas Orthoptera show an enormous range in sensitivity, from the most sensitive species tested, *Schistocerca gregaria,* at < 1 ppm to the least sensitive, *Melanoplus sanguinipes,* at > 1000 ppm (Mordue & Blackwell 1993).

Neem extracts (0.1 to 2%) are used in India for the protection of field crops and stored grains (Mordue & Blackwell 1993; Nigam et al. 1994). Topical applications of neem are effective for only 4–8 days, because azaridachtin breaks down in sunlight (Mordue & Blackwell 1993). Neem has proved more effective in protecting stored grain, where the protection may last for 'a number of months' (Mordue & Blackwell 1993) or a year (Nigam et al. 1994). Increasing concentrations of 0.5–4% neem oil showed increasing repellency to larvae of *Spodoptera litura* on urd bean (*Vigna mungo*) leaves (Venkateswarlu et al. 1988). A concentration of 8% neem oil was completely repellent. A concentration of 10% NeemAzal (containing 20% azadirachtin) reduced food consumption by larval American cockroaches (*Periplaneta americana*) by 60% and by adult female cockroaches by 75% (Richter et al. 1997). In New Zealand, a neem extract had antifeedant activity against the Australian carpet beetle (*Anthrenocerus australis*), the webbing clothes moth (*Tineola bisselliella*), and the casemaking clothes moth (*Tinea dubiella*) for at least 14 days at an azadirachtin concentration as low as 0.01% wool weight (Gerard et al. 1992).

Neem oil has been used as an insect repellent on humans. For example, 1–4% neem oil in coconut oil applied to exposed body parts of human volunteers gave up to 100% protection from *Anopheles* mosquito bites for 12 hours (Sharma et al. 1993, 1995; Mishra et al. 1995). Neemos (containing azadirachtin and citronella) provided protection from *Anopheles* mosquitoes for 8 hours (Caraballo 2000). A concentration of 2% neem oil in coconut oil gave 100% protection against *Phlebotomus* sandflies throughout the night (Sharma & Dhiman 1993).

Neem-based products are available on the market in a number of countries under trade names such as Azatin, Bioneem, Margosan-O, Neemark, NeemAzal, Neemesis, Neemgard, Neemos, Neemrich, Nimbosol, Repelin, Safer's ENI, and Wellgro (Mordue & Blackwell 1993; Nigam et al. 1994; Mulla & Su 1999; Caraballo 2000). Neemos also contains citronella (Caraballo 2000). Trade names available in New Zealand include NEEM 900 EC (containing at least 1500 ppm azadirachtin). The biological activity of neem preparations is closely related to their azadirachtin content (Warthen & Morgan 1990; Mordue & Blackwell 1993; Xie et al. 1995; Mulla & Su 1999).

Azadirachtin cannot be exploited commercially because of its large and complex chemical structure, which is both difficult and expensive to synthesise (Jain & Tripathi 1993; Mordue & Blackwell 1993; Srivastava et al. 1999). However, several isomers have been synthesised (Ley 1990 in Russell & Lane 1993). A readily synthesised tricylic furan that forms part of the azadirachtin structure is as deterrent to *Spodoptera littoralis* as azadirachtin (Blaney et al. 1990 in Russell & Lane 1993).

Vertebrate activity

Neem products are relatively safe to mammals and humans (Mulla & Su 1999). The acute oral LD_{50} of azadirachtin is > 5000 mg/kg for Norway rats (Tomlin 1994). Neem was repellent to starlings (*Sturnus vulgaris*) (Mason & Matthew 1996) and three species of Kenyan rodents (*Lemniscomys striatus*, *Mastomys natalensis*, and *Arvicanthis niloticus*) (Oguge et al. 1997). However, a commercial preparation of neem (Plasma Power P, India, containing at least 0.15% azadirachtin) applied at 2% on carrot baits (at least 0.003% azadirachtin) was not repellent to brushtail possums or laboratory Norway rats in a choice trial in New Zealand (T.D. Day, AgResearch, pers. comm.).

Availability

Neem oil is readily available and very cheap (Ascher 1992). In New Zealand it is available from Suntec (NZ) as NEEM 900 EC (containing at least 0.15% azadirachtin) for NZ$24/litre. However, azadirachtin is extremely expensive (A$72.50 for 500 μg in the Sigma 2000 catalogue).

13. Permethrin

Description

Permethrin is a synthetic pyrethroid, more stable to light and at least as active as natural pyrethrins (Budavari 1996). It is not as light-stable as other synthetic pyrethroids (e.g. cypermethrin, deltamethrin, and fenpropathrin). It is a yellow-brown liquid with a boiling point of > 290°C (Tomlin 1994).

Invertebrate activity

Permethrin is both an insecticide and an insect repellent (Brown & Herbert 1997; Cockcroft et al. 1998). It is effective against a wide range of invertebrates including lice, ticks, fleas, mites, mosquitoes, and black flies (Brown & Herbert 1997).

Permethrin is marketed in the USA as an insect repellent for human use, both as a cream and as an aerosol spray. It can be applied to the skin (1–5% in a cream), or sprayed on clothing, tents, netting, etc. It is effective for longer when applied to clothing than to skin. In a laboratory trial, permethrin was not as repellent to mosquites as DEET, but another pyrethroid (Pyrethroid-T, containing the alpha-cyano, 3-phenoxybenzyl moiety) was more repellent than DEET (Braverman & Chizov-Ginzburg 1997). Permethrin is not as repellent as cypermethrin, deltamethrin, and fenpropathrin (Thomson 1982).

Permethrin applied as a 0.015% spray reduced visits by Indian honeybees (*Apis cerana indica*) to radish crops for up to 8 days (Rathore et al. 1987). Baits treated with 0.04% permethrin repelled chrysomelid beetles (*Diabrotica speciosa*) for up to 14 days (Roel & Zatarin 1989). Apple paste bait containing 0.5% Ambush® 50 EC, a commercial formulation containing 5% permethrin (i.e. 0.025% permethrin in the bait) was repellent to honeybees, but also to brushtail possums (Morgan et al. 1993). However, emulsifiable concentrates often include aromatics that could make them unpalatable to possums.

Vertebrate activity

The acute oral LD_{50} of technical permethrin to Norway rats is 430–4000 mg/kg (Tomlin 1994). The palatability of technical permethrin to possums and rodents is unknown. However, in 2-year feeding trials, rats receiving 100 mg/kg diet showed no ill effects (Tomlin 1994), implying that permethrin is palatable to rats at that concentration.

Availability

Permethrin is readily available.

14. Pine oil

Description

Pine oil is extracted from certain *Pinus* species. It is a colourless to pale yellow liquid, with a turpentine-like odour. It has a boiling point of 200–220°C (Budavari 1996).

Invertebrate activity

Pine oil has invertebrate antifeedant properties. For example, oil from *Pinus sylvestris* was almost as repellent as DEET to ticks (*Ixodes persulcatus*) (Dobrotvorskii et al. 1989). Pine oil (unspecified) protected spruce (*Picea abies*) logs from attack by the striped ambrosia beetle (*Trypodendron lineatum*) (Coleoptera: Scolytidae) (Dubbel 1992), but did not protect *Pinus taeda*, *P. echinata*, or *P. virginiana* from attack by southern pine beetles (*Dendroctonus frontalis*), black turpentine beetles (*D. terebrans*), or *Ips grandicollis* (Nord et al. 1990). This latter result is not surprising because pines are the natural hosts of these beetles. Pine oil also repels mosquitoes (*Aedes* spp.) (Thorsell et al. 1998), house flies (*Musca domestica*) (Mananga et al. 1996), and onion maggots (*Delia antiqua*) (Ntiamoah et al. 1996).

Vertebrate activity

Pine oil is unpalatable to at least some rodents. Siberian pine (*Pinus sibirica*) needle oil reduced food consumption by deer mice (*Peromyscus maniculatus*) and prairie voles (*Microtus ochrogaster*) (Wager-Page et al. 1997). However, the palatability of pine oil to possums and the rodent species present in New Zealand is unknown.

Availability

Pine oil is readily available (e.g. from Essential Oils of New Zealand for NZ$206/ litre + GST).

15. Polygodial

Description

Polygodial is a drimane sesquiterpenoid originally isolated from the water-pepper plant, *Polygonum hydropiper*. It has subsequently been isolated from several plant genera, including *Warburgia* species (Norris 1986; Warthen & Morgan 1990) and the New Zealand native horopito (*Pseudowintera colorata*) (Gerard et al. 1992).

Invertebrate activity

Polygodial has been used experimentally in the UK to protect barley from the bird-cherry-oat aphid, *Rhopalosiphum padi*, a transmitter of barley yellow dwarf virus (Warthen & Morgan 1990; Jain & Tripathi 1993; Pickett et al. 1997; Srivastava et al. 1999). According to Pickett et al. (1997), polygodial has little antifeedant effect on beetles. However, it caused reduced feeding by the Colorado potato beetle (*Leptinotarsa decemlineata*) on potato leaf discs (Gols et al. 1996), and in New Zealand had antifeedant activity against the Australian carpet beetle (*Anthrenocerus australis*) at a concentration as low as 0.04% wool weight (Gerard et al. 1992). It also had both antifeedant and insecticidal activity against a lepidopteran, the webbing clothes moth (*Tineola bisselliella*) (Gerard et al. 1992).

Vertebrate activity

The palatability of polygodial to possums and rodents is unknown.

Availability

Polygodial has not been commercially developed, and is not readily available.

16. Pyrethrum

Description

Pyrethrum is a natural oil extract from the flowers of *Chrysanthemum* species, and contains a mixture of natural pyrethrins (Curtis et al. 1990; Tomlin 1994; Budavari 1996).

Invertebrate activity

Pyrethrum has been used as an indoor fumigant in the form of smoke or sprays for mosquito control. Powder formulations were once common both in domestic and agricultural use (Curtis et al. 1990). As well as being insecticidal, pyrethrum flushes invertebrates out from their hiding places. It was a more effective flushing agent against cockroaches than were synthetic pyrethroids such as cypermethrin and permethrin (Fuchs 1988). However, pyrethrum has little residual effect, and has largely been replaced by more effective synthetic chemicals (Curtis et al. 1990).

Vertebrate activity

The acute oral LD_{50} of pyrethrum to Norway rats is 1030–2370 mg/kg (Tomlin 1994). The palatability of pyrethrum to possums and rodents is unknown.

Availability

Pyrethrum is readily available.

17. Ugandensidial

Ugandensidial is a terpenoid derived from *Warburgia ugandensis* and other *Warburgia* species (Norris 1986; Warthen & Morgan 1990). It is active on *Spodoptera* species at 0.1 ppm (Warthen & Morgan 1990). However, it has not been commercially developed, and is not readily available.

18. Warburganal

Warburganal is a terpenoid derived from *Warburgia* species (Norris 1986; Warthen & Morgan 1990). It is twice as potent as azadirachtin (from neem oil) to *Spodoptera exempta* (Norris 1986; Warthen & Morgan 1990). However, it has not been commercially developed, and is not readily available.

19. Others

There are many other compounds also identified in the literature as invertebrate antifeedants (e.g. see Norris 1990; Warthen & Morgan 1990), too many to list within the constraints of the budget for this paper. For example, essential oils with insect repellent properties, other than those listed above, include bay, bergamot, cassia, clove, geranium, laurel, lavender, pennyroyal, peppermint, thyme, and wintergreen (Curtis et al. 1990; Thorsell et al. 1998). There are also many fungicides, acaricides, insecticides, and herbicides that are antifeedant to invertebrates (Ascher 1979; Thomson 1982; Hare & Moore 1988).

3.4 INVERTEBRATES LIKELY TO FEED ON BAITS AND COMPOUNDS LIKELY TO REPEL OR DETER THEM

The invertebrates most likely to eat baits used for vertebrate pest control in New Zealand include isopods (Isopoda), amphipods (Amphipoda), harvestmen (Opiliones), mites (Acarina), millipedes (Diplopoda), springtails (Collembola), cockroaches (Blattodea), earwigs (Dermaptera), weta (Orthoptera), beetles (Coleoptera), and ants (Hymenoptera) (Sherley et al. 1999; Spurr & Drew 1999; Lloyd & McQueen 2000). Compounds discussed in section 3.3 (above) and with antifeedant activity against these taxa are grouped by invertebrate taxon in Table 1. No references were found to antifeedants for amphipods, harvestmen, millipedes, springtails, or earwigs.

4. Discussion

Potential invertebrate antifeedants that could be added to baits used for vertebrate pest control that meet at least some of the criteria required include DEET, DMP, citronella oil, eucalyptus oil, neem oil, and alpha-cypermethrin. These are antifeedant to a broad spectrum of invertebrates, active at low concentrations, relatively low cost, and readily available. DEET is claimed to be the most effective insect repellent developed so far for human use (Brown & Herbert 1997; Chou et al. 1997; Qui et al. 1998). DMP, citronella oil, and eucalyptus oil are also insect repellents for human use. DMP has been also used as an invertebrate antifeedant in baits for small mammal trapping in the USA (Anderson & Ohmart 1977). Neem oil contains azadirachtin, claimed to be one of the most potent invertebrate antifeedants yet discovered (Jain & Tripathi

TABLE 1. ANTIFEEDANTS DISCUSSED IN SECTION 3.3 GROUPED BY INVERTEBRATE TAXA KNOWN TO EAT CEREAL BAITS.

INVERTEBRATE GROUP	ANTIFEEDANT	REFERENCES
Mites (Acarina)	Alpha-cypermethrin	Ahn et al. 1993
	Cinnamite[1]	Parrella et al. 1999
	Citrus oil	Ho & Fauziah 1993
	Cypermethrin	Cohen & Joseph 1992
	Diethyl toluamide (DEET)	Ho & Fauziah 1993
	Neem	Mansour et al. 1997; Momen et al. 1997
	Permethrin	Marshall & Pree 1991
Cockroaches (Blattodea)	Alpha-cypermethrin	Fuchs 1988; Terekhova 1995
	Cypermethrin	Ross & Cochran 1992
	Neem	Richter et al. 1997
	Permethrin	Fuchs 1988
	Pyrethrum	Fuchs 1988
Orthoptera	Cinnamon oil	Spurr & Drew 1999
(including weta)	Neem	Mordue & Blackwell 1993
Beetles (Coleoptera)	Camphor	Miles et al. 1985; Obeng et al. 1998
	Capsicum extracts	Ho et al. 1997
	Cinnamamide	Watkins 1996; Watkins et al. 1996
	Cinnamon oil	Oliveira & Vendramim 1999; Ho et al. 1997; Spurr & Drew 1999
	Cypermethrin	Hajjar & Ford 1990
	Eucalyptus oil	Yan & Tan 1998
	Muzigadial	Gerard et al 1992
	Neem	Gerard et al. 1992; Mordue & Blackwell 1993; Nigam et al. 1993; Xie et al. 1995
	Pine oil	Dubbel 1992 (but see Nord et al. 1990)
	Polygodial	Gerard et al. 1992 (but see Pickett et al.1997)
Ants (Formicidae)	Cinnamon oil	Spurr & Drew 1999
	Cypermethrin	Knight & Rust 1990
	Dimethyl phthalate (DMP)	Anderson & Ohmart 1977

[1] A synthesised analogue of cinnamon oil

1993; Mordue & Blackwell 1993; Nigam et al. 1994). Alpha-cypermethrin is a known invertebrate antifeedant, and is believed to be used as such in a commercially available rat bait.

Of the other potential invertebrate antifeedants, cinnamon oil (0.1–0.5%) is already added to baits used for possum control, to mask the smell and taste of 1080 to possums (Morgan 1990), although it is not added to baits used for rodent control (W. Simmons, ACP, pers. comm.). Cinnamon oil (0.1%) reduced the incidence of invertebrates feeding on baits by more than 50% for at least 3 days (Spurr & Drew 1999). A higher concentration of cinnamon oil (e.g. 0.3%) may reduce the incidence of invertebrates on baits even more, but may also reduce the palatability of baits to rats (Landcare Research, unpubl. data). However, a more effective invertebrate antifeedant is desired. Permethrin and cypermethrin are considered to be not as repellent as alpha-cypermethrin. Muzigadial, polygodial, ugandensidial, and warburganal are potent antifeedants against some invertebrates. However, they are not readily available and the likely cost of obtaining quantities sufficient for poisoning operations makes them impractical for this purpose. Capsaicin and cinnamamide are repellent to mammals, and would likely make baits unpalatable to possums and rats.

AgResearch (Hamilton) is developing a bird repellent that is palatable to possums and rats (T. Day, AgResearch, pers. comm.). Its composition has yet to be finalised, so it is not yet ready for testing against invertebrates.

The likely length of effectiveness of potential antifeedants to invertebrates is also difficult to estimate. The effectiveness of DEET, DMP, essential oils, and synthetic pyrethroids may be quite short-lived (a few hours), but formulation in a bait may increase their longevity (to several days). Invertebrate antifeedants are needed in toxic baits for as long as they remain available to invertebrates. For baits in bait stations, this could be several months.

There is little evidence available to identify what concentrations of invertebrate antifeedants should be added to baits used for vertebrate pest control. DEET is used in most insect repellents at concentrations of 20–30%, and in some at concentrations as low as 6%. DMP is also used in insect repellents at 20–30%, but was incorporated into baits used for trapping small mammals at 4% (Anderson & Ohmart 1977). Essential oils such as citronella and eucalyptus have been found to be feeding deterrents for Indian honeybees at 0.5–1% (Patayal & Kumar 1989). Neem oil has generally been used for protection of stored grain at 0.1–2% (Mordue & Blackwell 1993; Nigam et al. 1994). Permethrin, cypermethrin, and alpha-cypermethrin have generally been found to be deterrent to invertebrates at 0.02% to 0.2% (Roel & Zatarin 1989; Fisk & Wright 1992; Terekhova 1995).

The amount of invertebrate antifeedants that occur as liquids that can be added to baits used for vertebrate pest control is potentially restricted by the amount of liquid that can be absorbed by the baits. For cereal-based baits manufactured by Animal Control Products this is 2% (W. Simmons, ACP, pers. comm.). DEET, DMP, the essential oils, and commercially available formulations of alpha-cypermethrin all occur as liquids, although DEET can also be obtained in powder form. Thus, the maximum concentration of these compounds that can be added to cereal-based baits is 2%. This restriction is not present for invertebrate antifeedants (e.g. technical-grade alpha-cypermethrin) that are available as powders.

Currently, the main unknown in selecting potential invertebrate antifeedants for adding to baits used for vertebrate pest control is their palatability to possums and rats. This needs to be determined before invertebrate antifeedants can be used to prevent toxicants being transported into the environment by invertebrates.

In vertebrate pest control operations using bait stations, an alternative to incorporating invertebrate antifeedants into baits is to apply an insect repellent (such as in aerosol fly sprays or slow-release polymer strips) to the bait stations. This has the advantage that the compound would not have to be palatable to possums and rodents, although it would have to be non-repellent to them. Some research would be necessary to identify the best invertebrate repellent to use, both for acceptability to possums and rodents and for effectiveness against invertebrates. However, in the interim, this strategy could be implemented immediately in a research-by-management programme, using any commercially available fly spray or insect repellent polymer strip, with possible immediate conservation gains.

5. Recommendations

The following potential invertebrate antifeedants should be evaluated for palatability to possums and rats: DEET, DMP, citronella oil, eucalyptus oil, neem oil, and alpha-cypermethrin. Commercially available insect repellents (such as in aerosol fly sprays or slow-release polymer strips) should also be evaluated for use in bait stations to reduce invertebrate consumption of baits there.

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7. References

Aerts, R.J.; Mordue, A.J. 1997: Feeding deterrence and toxicity of neem triterpenoids. *Journal of Chemical Ecology 23*: 2117–2132.

Ahmad, R.; Sheikh, T.U.; Ahmad, A.; Ahmad, M. 1993: Essential oils as insect attractants and repellents. *Hamdard Medicus 36*: 99–105.

Ahn, Y.J.; Kwon, M.; Yoo, J.K.; Byun, S.J. 1993: Toxicity of flufenoxuron alone and in mixture with alphacypermethrin or fenbutain oxide to *Tetranychus urticae* and *Panonychus ulmi* (Acari: Tetranychidae). *Journal of Economic Entomology 86*: 1334–1338 (abstract only seen).

Anderson, B.W.; Ohmart, R.D. 1977: Rodent bait additive which repels insects. *Journal of Mammalogy 58*: 242.

Ascher, K.R.S. 1979: Fifteen years (1963–1978) of organotin antifeedants—a chronological bibliography. *Phytoparasitica 7*: 117–137.

Ascher, K.R.S. 1987: Plant-derived insect antifeedants: problems and prospects. *International Pest Control 29 (6):* 131–133.

Ascher, K.R.S. 1992: Antifeedants: an overview. *Philippine Entomologist 8*: 1117–1123.

Barratt, B.I.P.; Lorimer, S.D.; Perry, N.B.; Bashi-Hammer, M.; Foster, L.M.; Ferguson, C.M. 1993: A bioassay to evaluate native plant extracts as slug feeding deterrents. Proceedings of the Forty-sixth New Zealand Plant Protection Conference: 194–196.

Barrington, A.; Russell, G.B.; Lane, G.A. 1993: Effect of selected plants on the growth and development of leafrollers. Proceedings of the Forty-sixth New Zealand Plant Protection Conference: 187–190.

Bernays, E.A. 1983: Antifeedants in crop pest management. Pp. 259–271 in Whitehead, D.L.; Bowers, W.S. (Eds): Natural Products for Innovative Pest Management. Pergamon Press, Oxford.

Blank, R.H.; Bell, D.S.; McGhie, R.A. 1986: Field testing of seed protectants against black field cricket attack. Proceedings of the Thirty-ninth New Zealand Weed and Pest Control Conference: 22–26.

Boland, D.J.; Brophy, J.J 1993: Essential oils of the eucalypts and related genera. Pp. 72–87 in Teranishi, R.; Buttery, R.G.; Sugisawa, H. (Eds): Bioactive volatile compounds from plants. American Chemical Society, Washington DC, USA (abstract only seen).

Braverman, Y.; Chizov-Ginzburg, A. 1997: Repellency of synthetic and plant-derived preparations for *Culicoides imicola*. *Medical and Veterinary Entomology 11*: 355–360 (abstract only seen).

Brown, M; Herbert, A.A. 1997: Insect repellents: an overview. *Journal of the American Academy of Dermatology 36*: 243–249.

Brud, W.S.; Gora, J. 1990: Biological activity of essential oils and its possible applications. Pp. 13–23 in Proceedings of the 11th International Congress of Essential Oils, Fragrances and Flavours. New Delhi, India, 12–16 November, 1989. Vol. 2. Keynote presentations. Aspect Publishing, London, U.K. (abstract only seen).

Budavari, S. Ed. 1996: The Merck Index: an encyclopedia of chemicals, drugs, and biologicals. 12th edition. Merck, Whitehouse Station, NJ, USA. 1741 p + app.

Caraballo, A.J. 2000: Mosquito repellent action of Neemos®. *Journal of the American Mosquito Control Association 16*: 45–46 (abstract only seen).

Chabreck, R.H.; Constantin, B.; Hamilton, R.B. 1986: Use of chemical ant repellents during small mammal trapping. *Southwestern Naturalist 31*: 109–110.

Chapman, R.F. 1974: The chemical inhibition of feeding by phytophagous insects: a review. *Bulletin of Entomological Research 64*: 339–363.

Chou, J.T.; Rossignol, P.A.; Ayres, J.W. 1997: Evaluation of commercial insect repellents on human skin against *Aedes aegypti* (Diptera: Culicidae). *Journal of Medical Entomology 34*: 624–630.

Cockcroft, A.; Cosgrove, J.B.; Wood, R.J. 1998: Comparative repellency of commercial formulations of deet, permethrin and citronellal against the mosquito *Aedes aegypti*, using a collagen membrane technique compared with human arm tests. *Medical and Veterinary Entomology 12*: 289–294 (abstract only seen).

Cohen, E.; Joseph, T. 1992: Phagodeterrent response of the bulb mite *Rhizoglyphus robini* to various pyrethroids and some of their cleavage products. *Pesticide Science 35*: 125–129 (abstract only seen).

Coleman, R.H. 1950: DDT protects bait from ants. *Journal of Mammalogy 31*: 199.

Collins, D.A.; Brady, J.N.; Curtis, C.F. 1993: Assessment of the efficacy of Quwenling as a mosquito repellent. *Phytotherapy Research 7*: 17–20 (abstract only seen).

Crocker, D.R.; Scanlon, C.B.; Perry, S.M. 1993: Repellency and choice: feeding responses of wild rats (*Rattus norvegicus*) to cinnamic acid derivatives. *Applied Animal Behaviour Science 38*: 61–66.

Curtis, C.F.; Lines, J.D.; Lu Baolin; Renz, A. 1990: Natural and synthetic repellents. Pp. 75–92 in Curtis, C.F. (Ed.): Appropriate technology in vector control. CRC Press, Boca Raton, Florida, USA.

de Wael, L; van Laere, O. 1989: Toxicity and the repellent activity of synthetic pyrethroids towards the honeybee (*Apis mellifera* L.). Pp. 209–216 in Proceedings of the XXXIst International Congress of Apiculture, (abstract only seen).

Dobrotvorskii, A.K.; Tkachev, A.V.; Demenkova, L.I. 1989: [Study of the repellent activity of some plant extracts against *Ixodes persulcatus*]. Izvestiya Sibirskogo Otdeleniya Akademii Nauk SSSR. *Seriya Biologicheskikh Nauk 2*: 62–66 (Russian. English abstract only seen).

Dogan, E.B.; Ayres, J.W.; Rossignol, P.A. 1999: Behavioural mode of action of deet: inhibition of lactic acid attraction. *Medical and Veterinary Entomology 13*: 97–100.

Dubbel, V. 1992: The effectiveness of pine oil as a repellent against the striped ambrosia beetle *Trypodendron lineatum* (Col., Scolytidae). *Journal of Applied Entomology 114*: 91–97.

Eason, C.T.; Milne, L.; Potts, M.; Morriss, G.; Wright, G.R.G.; Sutherland, O.R.W. 1999: Secondary and tertiary poisoning risks associated with brodifacoum. *New Zealand Journal of Ecology 23*: 219–224.

Eason, C.T.; Murphy, E.C.; Wright, G.R.G.; Spurr, E.B. 2001: Risk assessment for second generation anticoagulant rodenticides, focusing on brodifacoum and birds. Pp. 75–96 in Shlosberg, A.; Bahat, O. (Eds): The risk of toxicoses from pesticides and pollutants in raptors and wildlife in Israel—the present situation and recommendations for the future. Proceedings of an international workshop, Jerusalem Biblical Zoo, Israel. Society for the Protection of Nature in Israel, Tel-Aviv, Israel.

Eason, C.T.; Murphy, E.C.; Wright, G.R.G.; Spurr, E.B. 2002: Assessment of risks of brodifacoum to non-target birds and mammals in New Zealand. *Ecotoxicology 11*: 35–48.

Fisk, T.; Wright, D.J. 1992: Comparative studies on acylurea insect growth regulators and neuroactive insecticides for the control of the army worm *Spodoptera exempta* Walk. *Pesticide Science 35*: 175–182 (abstract only seen).

Frances, S.P. 1994: Response of a chigger, *Eutrombicula hirsti* (Acari: Trombiculidae) to repellent and toxicant compounds in the laboratory. *Journal of Medical Entomology 31*: 628–630 (abstract only seen).

Fuchs, M.E.A. 1988: Flushing effects of pyrethrum and pyrethroid insecticides against the German cockroach (*Blattella germanica* L.). *Pyrethrum Post 17*: 3–7 (abstract only seen).

Gerard, P.J.; Ruf, L.D. 1991: Screening of plants and plant extracts for repellency to *Tinea dubiella*, a major New Zealand wool pest. Proceedings of the Forty-fourth New Zealand Weed and Pest Control Conference: 205–208.

Gerard, P.J.; Ruf, L.D.; Perry, N.B.; Foster, L.B. 1992: Insecticidal properties of the terpenoids polygodial, 9-deoxymuzigadial and azadirachtin. Proceedings of the Forty-fifth New Zealand Plant Protection Conference: 239–242.

Gerard, P.J.; Rohitha, B.H.; Perry, N.B.; Ruf, L.D.; Karl, A.K.; Foster, L.M. 1993: Antifeedant and insecticidal activity of some New Zealand gymnosperms. Proceedings of the Forty-sixth New Zealand Plant Protection Conference: 191–193.

Gettinger, R.D. 1990: Effects of chemical insect repellents on small mammal trapping yield. *American Midland Naturalist 124*: 181–184.

Golenda, C.F.; Solberg, V.B.; Burge, R.; Gambel, J.M.; Wirtz, R.A. 1999: Gender-related efficacy difference to an extended duration formulation of topical N,N-diethyl-m-toluamide (DEET). *American Journal of Tropical Medicine and Hygiene 60*: 654–657.

Golley, F.B. 1961: Trap and bait preference of cotton rats. *Journal of Mammalogy 42*: 106–107.

Gols, G.J.Z.; van Loon, J.J.A.; Messchendorp, L. 1996: Antifeedant and toxic effects of drimanes on Colorado potato beetle larvae. *Entomologia Experimentalis et Applicata 79*: 69–76.

Goodwin, R.M.; Ten Houten, A. 1991: Poisoning of honey bees (*Apis mellifera*) by sodium monofluoroacetate (1080) in baits. *New Zealand Journal of Zoology 18*: 45–51.

Gurney, J.E.; Watkins, R.W.; Gill, E.L.; Cowan, D.P. 1996: Non-lethal mouse repellents: evaluation of cinnamamide as a repellent against commensal and field rodents. *Applied Animal Behaviour Science 49*: 353–363.

Hajjar, M.J.; Ford, J.B. 1990: The effect of cypermethrin on the feeding of mustard beetles *Phaedon cochleariae* (F.). *Annals of Applied Biology 116*: 279–286 (abstract only seen).

Hare, D.J.; Moore, R.B.E. 1988: Impact and management of late-season populations of the Colorado potato beetle (Coleoptera: Chrysomelidae) on potato in Connecticut. *Journal of Economic Entomology 81*: 914–921.

Ho, S.H.; Ma, Y.; Tan, H.T.W.; Halid, H. 1997: Repellency of some plant extracts to the stored products beetles, *Tribolium castaneum* (Herbst) and *Sitophilus zeamais* Motsch. Proceedings of the symposium on pest management for stored food and feed. *BIOTROP Special Publication 59*: 209–215 (abstract only seen).

Ho, T.M.; Fauziah, M.K. 1993: Laboratory evaluation of two commercial repellents against *Leptotrombidium fletcheri* (Acari: Trombiculidae). *Southeast Asean Journal of Tropical Medicine and Public Health 24*: 165–169.

Huang, Y.; Ho, S.H. 1998: Toxicity and antifeedant activities of cinnamaldehyde against the grain storage insects, *Tribolium castaneum* (Herbst) and *Sitophilus zeamais* Motsch. *Journal of Stored Products Research 34*: 11–17 (abstract only seen).

Hubert, T.D.; Wiemer, D.F. 1985: Ant-repellent terpenoids from *Melampodium divaricatum*. *Phytochemistry 24*: 1197–1198 (abstract only seen).

Husain, M.M.; Mondal, K.A.M.S.H.; Ali, S.H.; Rahim, A. 1994: Repellent effect of diazinon on larval *Tribolium confusum* Duval. *Bangladesh Journal of Scientific and Industrial Research 29*: 41–45 (abstract only seen).

Ignatowicz, S. 1997: Powdered herbs of the mint family (Lamiaceae) as insect repellents for protection of stored wheat grain. *Polskie Pismo Entomologiczne 66*: 135–149 (abstract only seen).

Innes, J.; Barker, G. 1999: Ecological consequences of toxin use for mammalian pest control in New Zealand—an overview. *New Zealand Journal of Ecology 23*: 111–127.

Jain, D.C.; Tripathi, A.K. 1993: Potential of natural products as insect antifeedants. *Phytotherapy Research 7*: 327–334.

Jermy, T. 1983: Multiplicity of insect antifeedants in plants. Pp. 223–236 in Whitehead, D.L.; Bowers, W.S. (Eds): Natural products for innovative pest management. Pergamon Press, Oxford.

Jermy, T. 1990: Prospects of antifeedant approach to pest control—a critical review. *Journal of Chemical Ecology 16*: 3151–3166.

Kalyanasundaram, M.; Srinivasan, R.; Subramanian, S.; Panicker, K.N. 1994: Relative potency of DEPA as a repellent against the sandfly *Phlebotomus papatasi. Medical and Veterinary Entomology 8*: 68–70 (abstract only seen).

Khan, M.; Shahjahan, R.M. 1998: Evaluation of eucalyptus leaf extracts as repellent for adult *Sitophilus oryzae* (L.) (Col.: Curculionidae) and attractant for *Callosobruchus chinensis* (L.) (Col.: Bruchidae). *Bangaladesh Journal of Entomology 8*: 81–88 (abstract only seen).

Knight, R.L.; Rust, M.K. 1990: Repellency and efficacy of insecticides against foraging workers in laboratory colonies of Argentine ants (Hymenoptera: Formicidae). *Journal of Economic Entomology 83*: 1402–1408.

Kumar, S.; Prakash, S.; Rao, K.M. 1995: Comparative activity of three repellents against bedbugs *Cimex hemipterus* (Fabr.). *Indian Journal of Medical Research 102*: 20–23.

Lale, N.E.S. 1991: The biological effects of three essential oils on *Callosobruchus maculatus* (F.) (Coleoptera: Bruchidae). *Journal of African Zoology 105*: 357–362. (only abstract seen)

Lin, T.S. 1998: [Effects of essential oil from the leaves of seven *Eucalyptus* on the control of termite]. *Forest Products Industries 17*: 751–760. (Chinese, English abstract only seen)

Lindsay, L.R.; Surgeoner, G.A.; Heal, J.D.; Gallivan, G.J. 1996: Evaluation of the efficacy of 3% citronella candles and 5% citronella incense for protection against field populations of *Aedes* mosquitoes. *Journal of the American Mosquito Control Association 12*: 293–294 (abstract only seen).

Lloyd, B.D.; McQueen, S.M. 2000: An assessment of the probability of secondary poisoning of forest insectivores following an aerial 1080 possum control operation. *New Zealand Journal of Ecology 24*: 47–56.

Mananga, M.E.; Gries, G.; Gries, R. 1996: Repellency of various oils and pine oil constituents to house flies (Diptera: Muscidae). *Environmental Entomology 25*: 1182–1187 (abstract only seen).

Mansour, F.A.; Ascher, K.R.S.; Abo-Moch, F. 1997: Effects of Neemguard on phytophagous and predacious mites and on spiders. *Phytoparasitica 25*: 333–336 (abstract only seen).

Marshall, D.B.; Pree, D.J. 1991: Effects of miticides on the life stages of the European red mite, *Pananychus ulmi* (Koch) (Acari: Tetranychidae). *Canadian Entomologist 123*: 77–87 (abstract only seen).

Mason, J.R. 1988: Mammal repellents: options and considerations for development. Pp. 325–329 in Baker, R.O.; Crabb, A.C. (Eds): Proceedings of the 18th vertebrate pest conference, University of California, Davis, California, USA.

Mason, J.R.; Matthew, D.N. 1996: Evaluation of neem as a bird repellent chemical. *International Journal of Pest Management 42*: 47–49.

Mason, J.R.; Bean, N.J.; Shah, P.S.; Clark, L. 1991: Taxon-specific differences in responsiveness to capsaicin and several analogues: correlates between chemical structure and behavioral aversiveness. *Journal of Chemical Ecology 17*: 2539–2551.

Mayeux, J.V. 1996: Hot shot insect repellent: an adjuvant for insect control. P. 35 in Proceedings Beltwide Cotton Conferences, Nashville, TN, USA, January 9–12, 1996, Vol. 1. (abstract only seen).

Miles, D.H.; Hankinson, B.L.; Randle, S.A. 1985: Insect antifeedants from the Peruvian plant *Alchornea triplinervia*. Pp. 469–476 in Hedin, P.A. (Ed.): Bioregulators for pest control. American Chemical Society, Washington, DC, USA. *ACS Symposium Series 276* (abstract only seen).

Mishra, A.K.; Neeru, S; Sharma, V.P.; Singh, N. 1995: Use of neem oil as a mosquito repellent in tribal villages of Mandla District, Madhya Pradesh. *Indian Journal of Malariology 32*: 99–103 (abstract only seen).

Momen, F.M.; Reda, A.S.; Amer, S.A.A. 1997: Effect of Neem Azal-F on *Tetranychus urticae* and three predacious mites of the family Phytoseiidae. *Acta Phytopathologica et Entomologica Hungarica 32*: 355–362 (abstract only seen).

Mordue, A.J.; Blackwell, A. 1993: Azadirachtin: an update. *Journal of Insect Physiology 39*: 903–924.

Morgan, D.R. 1990: Behavioural response of brushtail possums, *Trichosurus vulpecula*, to baits used in pest control. *Australian Wildlife Research 17*: 601–613.

Morgan, D.R.; Goodwin, M.; Henderson, R.J.; Perry, J. 1993: Identification of a bee repellent for use in possum paste: preliminary results. Landcare Research contract report LC9293/120 (unpublished). Landcare Research, Lincoln, New Zealand. 16 p.

Mulla, M.S.; Su, T. 1999: Activity and biological effects of neem products against arthropods of medical and veterinary importance. *Journal of the American Mosquito Control Association 15*: 133–152 (abstract only seen).

Mumcuoglu, K.Y.; Galun, R.; Bach, U.; Miller, J.; Magdassi, S. 1996: Repellency of essential oils and their components to the human body louse, *Pediculus humanus humanus. Entomologia Experimentalis et Applicata 78*: 309–314.

Nigam, S.K.; Misra, G.; Sharma, A. 1994: Neem: a promising natural insecticide. *Applied Botany Abstracts 14*: 35–46.

Nord, J.C.; Hastings, F.L.; Jones, A.S. 1990: Field tests of pine oil as a repellent for southern pine bark beetles. Research Note Southeastern Forest Experiment Station, USDA Forest Service No. SE-355, 8 p. (abstract only seen).

Norris, D.M. 1986: Anti-feeding compounds. Pp. 97–146 in Haug, G.; Hoffman, H. (Managing Eds) and Bowers, W.S.; Ebing, W.; Fakuto, T.R.; Martin, D.; Wegler, R.; Yamamoto, T. (Eds): Chemistry of Plant Protection. 1. Sterol biosynthesis, inhibitors and anti-feeding compounds. Springer Verlag, Berlin.

Norris, D.M. 1990: Repellents. Pp. 135–149 in Morgan, E.D.; Mandava, N.B. (Eds): CRC handbook of natural pesticides, volume VI: insect attractants and repellents. CRC Press, Boca Raton, Florida, USA.

Ntiamoah, Y.A.; Borden, J.H.; Pierce, H.D. 1996: Identity and bioactivity of oviposition deterrents in pine oil for the onion maggot, *Delia antiqua. Entomologia Experimentalis et Applicata 79*: 219–226 (abstract only seen).

Obeng, O.D.; Reichmuth, C.H.; Bekele, A.J.; Hassanali, A. 1998: Toxicity and protectant potential of camphor, a major component of essential oil of *Ocimum kilimandscharicum*, against four stored product beetles. *International Journal of Pest Management 44*: 203–209 (abstract only seen).

O'Connor, B. (Ed.). 2000: Novachem manual 2000/2001. A New Zealand guide to agrichemicals for plant protection. Novachem Services, Palmerston North, New Zealand. 452 p.

Oguge, N.; Ndung'u, D.; Okemo, P. 1997: Effects of neem plant (*Azadirachta indica* Juss, Meliaceae) products on maize grain consumption by three common rodent pests in Kenya. *Belgian Journal of Zoology 127 (supplement 1)*: 129–135.

Oliveira, J.V.; Vendramim, J.D. 1999: Repelencia de oleos essenciais e pos vegetais sobre adultos de *Zabrotes subfasciatus* (Boh.) (Coleoptera: Bruchidae) em sementes de feijoeiro. *Anais da Sociedade Entomologica do Brasil 28*: 549–555. (English abstract only seen).

Parrella, M.P.; von Damm, K.D.; von Damm, K.G.; Murphy, B. 1999: Cinnamite: the ideal reduced-risk pesticide? *Grower Talks 63*: 82–90 (abstract only seen).

Patyal, S.K.; Kumar, J. 1989: Olfacto-gustatory repellency of some essential oils to the Indian honey bee, *Apis cerana indica* Fabr. *Indian Bee Journal 51*: 5–8 (abstract only seen).

Pickett, J.A.; Wadhams, L.J.; Woodcock, C.M. 1997: Developing sustainable pest control from chemical ecology. *Agriculture, Ecosystems and Environment 64*: 149–156.

Qui, H.; Jun, H.W.; McCall, J.W. 1998: Pharmacokinetics, formulation, and safety of insect repellent N,N-diethyl-3-methylbenzamide (deet): a review. *Journal of the American Mosquito Control Association 14*: 12–27.

Rathore, R.R.S.; Reddy, M.L.K.; Sachan, G.C. 1987: Effect of insecticidal sprays on the visits of Indian honey bee, *Apis cerana indica* Fab. on radish crop. *Cruciferae Newsletter 1987 No. 12*: 93 (abstract only seen).

Richter, K; Bohm, G.A.; Kleeberg, H. 1997: Effect of NeemAzal, a natural azadirachtin-containing preparation, on *Periplaneta americana* (L.) (Orthopt., Blattidae). *Journal of Applied Entomology 121*: 59–64.

Riedl, H.; Shearer, P.W. 1991: Double-leaf-disk residue assay for assessing the toxicity of repellent acaricides to spider mites (Acari: Tetranychidae). *Experimental and Applied Acarology 11*: 149–157 (abstract only seen).

Robinson, W.H.; Barlow, R.A.; Rambo, G.W. 1999: Efficacy of a cockroach control bait exposed to insecticides. Pp. 121–125 in Proceedings of the 3rd International Conference on Urban Pests. (abstract only seen).

Roel, A.R.; Zatarin, M. 1989: [Efficacy of water pumpkin (*Lagenaria vulgaris* Cucurbitacea) baits treated with insecticides on attractiveness to *Diabrotica speciosa* (Germar, 1824) (Coleoptera: Chrysomelidae)]. *Anais da Sociedade Entomologica do Brasil 18*: 213–219 (in Portuguese: English abstract only seen).

Roese, J. 1984: Dimethyl phthalate as an additive to bait for small mammals to repel insects. MSc thesis (unpublished), Stephen F. Austin State University, Austin, Texas, USA. 51 p (not seen).

Ross, M.H.; Cochran, D.G. 1992: Strain differences in the response of German cockroaches (Dictyoptera: Blattellidae) to emulsifiable concentrates. *Journal of Economic Entomology 85*: 1201–1208.

Russell, G.B. 1986: Phytochemical resources for crop protection. *New Zealand Journal of Technology 2*: 127–134.

Russell, G.B.; Lane, G.A. 1993: Insect antifeedants—a New Zealand perspective. Proceedings of the Forty-sixth New Zealand Plant Protection Conference: 179–186.

Rutledge, L.C.; Gupta, R.K.; Mehr, Z.A.; Buescher, M.D.; Reifenrath, W.G. 1996: Evaluation of controlled-release mosquito repellent formulations. *Journal of the American Mosquito Control Association 12*: 39–44 (abstract only seen).

Salafsky, B; Ramaswamy, K.; He, Y.X.; Li, J.; Shibuya, T. 1999: Development and evaluation of LIPODEET, a new long-acting formulation of N,N-diethyl-m-toluamide (DEET) for the prevention of schistosomiasis. *American Journal of Tropical Medicine and Hygiene 61*: 743–750 (abstract only seen).

Satoh, A.; Utamura, H.; Nakade, T.; Nishimura, H. 1995: Absolute configuration of a new mosquito repellent, (+)-eucamalol and the repellent activity of its epimer. *Bioscience, Biotechnology and Biochemistry 59*: 1139–1141 (abstract only seen)

Schmutterer, H. 1990: Properties and potential of natural pesticides from the neem tree, *Azadirachta indica. Annual Review of Entomology 35*: 271–297 (abstract only seen).

Schoonhoven, L.M. 1982: Biological aspects of antifeedants. *Entomologia Experimentalis et Applicata 31*: 57–69.

Sharma, S.K.; Dua, V.K; Sharma, V.P. 1995: Field studies on the mosquito repellent action of neem oil. *Southeast Asian Journal of Tropical Medicine and Public Health 26*: 180–182 (abstract only seen).

Sharma, V.P.; Dhiman, R.C. 1993: Neem oil as a sandfly (Diptera: Psychodidae) repellent. *Journal of the American Mosquito Control Association 9*: 364–366 (abstract only seen).

Sharma, V.P.; Ansari, M.A.; Razdan, R.K. 1993: Mosquito repellent action of neem (*Azadirachta indica*) oil. *Journal of the American Mosquito Control Association 9*: 359–360 (abstract only seen).

Sherley, G.; Wakelin, M.; McCartney, J. 1999: Forest invertebrates found on baits used in pest mammal control and the impact of sodium monofluoroacetate (“1080”) on their numbers at Ohakune, North Island, New Zealand. *New Zealand Journal of Zoology 26*: 279–302.

Shorey, H.H.; Gaston, L.K.; Gerber, R.G.; Sisk, C.B.; Phillips, P.A. 1996: Formulating farnesol and other ant-repellent semiochemicals for exclusion of Argentine ants (Hymenoptera: Formicidae) from citrus trees. *Environmental Entomology 25*: 114–119.

Sigma 2000: Biochemicals and reagents for life science research. Sigma-Aldrich Co., Castle Hill, NSW, Australia. 2848 p.

Spurr, E.B. 1994: Impacts on non-target invertebrate populations of aerial application of sodium monofluoroacetate (1080) for brushtail possum control. In Seawright, A.A.; Eason, C.T. (Eds.): Proceedings of the science workshop on 1080. *The Royal Society of New Zealand Miscellaneous Series 28*: 116–123.

Spurr, E.B. 1996a: Environmental effects of rodent Talon® baiting. Part II: Impacts on invertebrate populations. Pp.12–27 in *Science for Conservation 38*. Department of Conservation, Wellington, New Zealand.

Spurr, E.B. 1996b: Carbohydrate bait preferences of wasps (*Vespula vulgaris* and *V. germanica*) (Hymenoptera: Vespidae) in New Zealand. *New Zealand Journal of Zoology 23*: 315–324.

Spurr, E.B. 2000: Impacts of possum control on non-target species. Pp. 175–186 in Montague, T.L. (Ed.): The brushtail possum—biology, impact and management of an introduced marsupial. Manaaki Whenua Press, Lincoln, New Zealand.

Spurr, E.B.; Drew, K.W. 1999: Invertebrates feeding on baits used for vertebrate pest control in New Zealand. *New Zealand Journal of Ecology 23*: 167–173.

Spurr, E.B.; Porter, R.E.R. 1998: Cinnamamide as a bird repellent for baits used in mammalian pest control. Pp. 295–299 in Proceedings, Australian Vertebrate Pest Conference 11.

Srivastava, R.; Shukla, Y.N.; Kumar, S. 1999: Recent advances in the chemistry of insect antifeedants. *Journal of Medicinal and Aromatic Plant Sciences 21*: 59–76.

Szentesi, A.; Jermy, T. 1985: Antifeedants of the Colorado potato beetle: an overview and outlook. Pp. 17–27 in Ferro, D.N.; Voss, R.H. (Eds): Proceedings, Symposium on the Colorado Potato Beetle. Massachussetts Agricultural Experiment Station, University of Massachussetts, Amherst, Research Bulletin 704.

Terekhova, Z.A. 1995: [Insecticidal gel, a promising form of pyrethroid application]. *Meditsinskaya Parazitologiya i Parazitarnye Bolezni 1*: 29–32 (Russian; English abstract only seen).

Thomson, W.T. 1982: Agricultural Chemicals. Book 1. Insecticides, acaricides, and ovicides. Thomson Publications, Fresno, California, USA. 249 p.

Thorsell, W.; Mikiver, A.; Malander, I.; Tunon, H. 1998: Efficacy of plant extracts and oils as mosquito repellents. *Phytomedicine 5*: 311–323.

Tomlin, C. 1994: The Pesticide Manual, incorporating the agrochemicals handbook. A world compendium. 10th Edition. British Crop Protection Council, Farnham, U.K. 1341 p.

Trigg, J.K. 1996a: Evaluation of eucalyptus-based repellent against *Anopheles* spp. in Tanzania. *Journal of the American Mosquito Control Association 12 (2, Part 1)*: 243–246. (abstract only seen).

Trigg, J.K. 1996b: Evaluation of eucalyptus-based repellent against *Culicoides impunctatus* (Diptera: Ceratopogonidae) in Scotland. *Journal of the American Mosquito Control Association 12 (2, Part 1)*: 329–330 (abstract only seen).

Trigg, J.K.; Hill, N. 1996: Laboratory evaluation of a eucalyptus-based repellent against four biting arthropods. *Phytotherapy Research 10*: 313–316 (abstract only seen).

Venkateswarlu, P.; Raghavaiah, G.; Nagalingam, B. 1988: Effect of neem oil on certain behavioural aspects of *Spodoptera litura* Fabricius in urdbean. *Indian Journal of Pulses Research 1*: 118–123 (abstract only seen).

Vigneron, J.-P. 1978: Substances antiappétantes d'origine naturelle. *Annales Zoologie Ecologie Animale 10*: 663–694.

Wager-Page, S.A.; Epple, G.; Mason, J.R. 1997: Variation in avoidance of Siberian pine needle oil by rodent and avian species. *Journal of Wildlife Management 61*: 235–241.

Warthen, J.D.; Morgan, E.D. 1990: Insect feeding deterrents. Pp. 23–134 in Morgan, E.D.; Mandava, N.B. (Eds): CRC handbook of natural pesticides, volume VI: insect attractants and repellents. CRC Press, Boca Raton, Florida, USA.

Watanabe, K.; Y. Shono, Y.; Kakimizu, A.; Okada, A.; Matsuo, N.; Satoh, A.; Nishimura, H. 1993: New mosquito repellent from *Eucalyptus camaldulensis*. *Journal of Agricultural and Food Chemistry 41(11)*: 2164–2166.

Watkins, R.W. 1996: Efficacy of cinnamamide as a repellent for vertebrate and invertebrate pests. *Pesticide Outlook 7 (4)*: 21–24.

Watkins, R.W.; Mosson, H.J.; Gurney, J.E.; Cowan, D.P.; Edwards, J.P. 1996: Cinnamic acid derivatives: novel repellent seed dressings for the protection of wheat seed against damage by the field slug, *Deroceras reticulatum. Crop Protection 15*: 77–83.

Xie, Y.S.; Fields, P.G.; Isman, M.B. 1995: Repellency and toxicity of azadirachtin and neem concentrates to three stored-product beetles. *Journal of Economic Entomology 88*: 1024–1031 (abstract only seen).

Yan, A.J.; Tan, Q. 1998: Repellency effects of essential oil derived from Eucalyptus leaf against three species of sawyers. *Journal of Nanjing Forestry University 22*: 87–90 (abstract only seen).

Yap, H.H.; Jahangir, K.; Chong, A.S.C.; Adanan, C.R.; Chong, N.L.; Malik, Y.A.; Rohaizat, B. 1998: Field efficacy of a new repellent, KBR 3023, against *Aedes albopictus* (Skuse) and *Culex quinquefasciatus* (Say) in a tropical environment. *Journal of Vector Ecology 23*: 62–68 (abstract only seen).

Appendix 1

NUMBER OF REFERENCES RETRIEVED USING VARIOUS SEARCH TERMS IN OCTOBER 2000

SEARCH TERM	CAB ABSTRACTS 1990–2000	CURRENT CONTENTS 1991–2000	AGRICOLA 1970–2000
insect* repellent*	724	114	194
insect* suppressant*	0	0	6
insect* deterrent*	9	1	87
insect* antifeedant*	172	108	174
insect* inhibitor*	24	7	272
invertebrate* repellent*	1	0	0
invertebrate* suppressant*	0	0	0
invertebrate* deterrent*	0	0	3
invertebrate* antifeedant*	0	0	0
invertebrate* inhibitor*	0	0	8
arthropod* repellent*	8	11	6
arthropod* suppressant*	0	0	0
arthropod* deterrent*	0	0	2
arthropod* antifeedant*	0	0	1
arthropod* inhibitor*	0	0	10

* Code in CAB Abstracts allowing search for expanded words (e.g. insects, insecticide, insecticidal). The code is $ in Current Contents. Expanded words and phrases are not available in Agricola, so the first search term above, for example, is for the two words ‘insect’ and ‘repellent’, not for the phrases ‘insect repellent’, ‘insect repellents’ etc.