REVIEW ARTICLE

# A review of chemical control options for invasive social insects in island ecosystems

M. C. Gentz

Division of Chemical and Structural Biology, Institute for Molecular Bioscience, University of Queensland, St. Lucia, Queensland, Australia

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**Correspondence**
Margaret C. Gentz (corresponding author), Institute for Molecular Bioscience, University of Queensland, 306 Carmody Road, St Lucia, Qld 4072, Australia.
E-mail: m.gentz@imb.uq.edu.au

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## Abstract

Social insects present unique challenges to chemically based management strategies, especially because fast-acting compounds commonly applied for many pest insects may not be the most effective for colony elimination. The reproductive caste of a colony is the most protected from direct damage by insecticides, and compounds that cause rapid mortality among foragers frequently do not impact the reproductive members or even markedly reduce overall colony size. With recent bans on persistent insecticides that previously have been used to control social insects, especially termites, new compounds must be used. Island and coastal ecosystems are particularly sensitive to the effects of widespread pesticide use and concerns about unintentional water pollution and runoff are common, and international attention is being paid to developing sustainable pesticide options for agricultural and urban pest insects in particularly sensitive environments. Given the precarious status of many native insects and arthropods care must be taken to minimize exposure to potentially harmful insecticides and the non-target impacts of these chemicals. However, recent developments in the synthesis and discovery of highly selective insecticides with low mammalian and non-target toxicity provide viable alternatives to the broad-spectrum persistent organochlorine insecticides that have been largely deregistered. Novel technologies, particularly synthetic analogues of biologically active compounds, yield new chemical control options and management strategies for island and other sensitive ecosystems; case studies from Australia, the Galapagos Islands and New Zealand highlight current challenges and successes.

## Introduction

Isolated island habitats have different concerns about invasive and alien species than connected continental areas, including wariness of transgressions against quarantine regulations and the protection of native species with limited geographic range (OTA 1993; Thaman 2002). Given the elevated threat of the establishment of species with ecologies unlike endemic taxa, large-scale control measures, both chemical- and biocontrol-based, for established invasive species have been portrayed as environmentally unappealing. Recent advances in physiology, synthetic and formulation chemistry and ecology, have provided effective alternatives to more persistent broad-spectrum control compounds and highlighted the role chemicals can play in the management and control of alien eusocial insects, in particular with the introduction of bait systems and an increased understanding of colony structure.

Islands, estuaries and coastal areas respond differently to pesticides than do continental areas, due in part to low levels of groundwater, concerns about pesticide runoff into water systems and geographic factors such as climate and altitude that can contribute dramatically to pesticide persistence (Scott et al. 2002; Villa et al. 2003). Volcanic islands, characterized by porous rock and thin soil, are particularly susceptible to groundwater contamination. This is particularly problematic because these basal aquifers are often the major source of drinking water on islands. In Hawaii, for example, over 90% of the drinking water comes from groundwater (EPA 2007); in Australia, groundwater makes up roughly 17% of available water resources but accounts for over 30% of total water consumption (National Water Commission 2008). The high frequency of extreme events and natural disasters, deforestation and habitat degradation add to environmental conditions that magnify the impact of invasive species (Castillo et al. 1997). Tropical islands offer the additional benefits of consistently warm weather and high humidity, allowing many temperate invaders to be active year-round (Sutherst 2000).

Prevention remains the primary mechanism to limit the number of introduced non-indigenous species, but funding allocations to limit the number of breaches have not followed increases in trade and tourism. For example, Hawaii is the only state in the United States where all passengers and cargo to other states are subject to clearance by Federal agricultural inspectors; the high volume of military traffic and nearby California's large agricultural industry have been cited as justifications for this activity (OTA 1993). One proposed mechanism of paying for the increased screening cost was the 'tourist tax', which would have levied a fee on passengers and vessels leaving the islands. This measure was ultimately blocked by the Hawaii Congressional Delegation because it was perceived as benefiting the continental United States at the expense of Hawaii's residents and tourists (OTA 1993). Although eradication is the ultimate goal of every counter-invasive species programme, it is often not practical because of the need for public and economic support, the absence of appropriate treatment options and widespread infestation of the invader before detection. The long-standing pest prevention and control programmes of New Zealand and Australia have been used as instructive models for the United States (OTA 1993); however, when prevention fails chemical control can provide viable pathways for reduced-risk towards management and eradication plans for invasive species.

## Management principles

Chemical control, cultural control (or interference) and biological control are the three primary options for the management of introduced species – and each comes with challenges in the implementation of the plan and continued programme sustainability. In this paper, cultural control and interference are defined as types of programmes that modify the habitat or landscape so it becomes unsuitable for the insect to colonize or inhabit long-term; other techniques, like soil barriers or bait systems, are classified as chemical control (Dent 2000).

To effectively manage and control introduced social insects different programmes must be initiated than for other pestiferous arthropods because of dramatic differences in ecology and behaviour (Wilson 1987). Social insects further complicate both localized and large-scale management due to their complex interactions with each other and their environment, and frequently expansive colonies (Moller 1996). The caste system precludes reproductive members of the colony from high levels of exposure to poisons that target foragers and to invaders the defensive members fight. Usually, programmes tailored to specific environments for each invader are needed; for example, tramp ants have been a target of Australia's Threat Abatement Plan (Commonwealth of Australia 2006a,b) and an eradication programme in the Galapagos Islands designed to minimize the impact on endemic species and biodiversity (Causton et al. 2005).

The success of a cultural control or interference programme is based on vigilance and may come with a significant financial burden associated with monitoring (Myers et al. 1998). These approaches are purely prophylactic and work best when used in conjunction with other practices to control colonizers on arrival. Methods popular with agricultural integrated pest management (IPM) strategies, like sterilized insect techniques and changes to agricultural practices or modifications of the planting landscape, are largely not appropriate for social insects because the treatments fail to affect the reproductives. Colonies of social insects, where reproductives, foragers, and soldiers can be replaced require sophisticated methods to isolate and injure the reproductives. Barrier methods have been proposed to prevent subterranean termite infestation, for example installing stainless steel mesh around possible entry points into the structure (e.g. plumbing outlets), and cement slabs or rock particle barriers underneath a building (Su and Scheffrahn 1998).


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Borate-treated timber has been shown to be an effective deterrent to attack by the Formosan subterranean termite, *Coptotermes formosanus* Shiraki (Isoptera: Rhinotermitidae), and the boron formulation seems not to impact toxicity (Gentz and Grace 2006, 2007; Campora and Grace 2007). These physical barriers, when installed correctly, can be long-term non-specific solutions, but must be put in place during construction and most are not options for existing structures or the eradication of rapidly spreading introduced exotic species.

The importation of classical biological control agents has had a controversial history worldwide, and have created particular problems for island ecosystems (Howarth 1991). Because of the cryptic nature and colony defence and grooming behaviours of social insects, commercially viable natural enemy-based management tools for these pests have not yet been released. At this point, there have not been examples of success with a biocontrol agent for use with invasive ants (Gilbert and Patrock 2002), though recent work by Estrada et al. (2006) with phorid flies (Diptera: *Pseudacteon* spp.) that are parasitoids of the Red Imported Fire Ant (*Solenopsis invicta* Buren) in their native Argentina has shown promise based on attack rates and host specificity. However, successful parasitism with this biocontrol agent has yet to be established in the laboratory under conditions similar to those of the newly invaded range. Modification of microbial natural enemies for management of termites has also yielded promising data from bacteria (Husseneder and Grace 2005), as have entomopathogenic nematodes (Mankowski et al. 2005) and strains of the fungi *Metarhizium* and *Beauveria* (Culliney and Grace 2000; Rath 2000; Wright et al. 2005), but these products are not yet commercially available on the global market.

### Recent advances in reduced-risk synthetic insecticides

Chemical control has benefited in large part from newer, synthetic compounds with precise mechanisms of action and largely decreased toxicity to non-target organisms. Theories were common about pesticide treatments – and insecticide use in particular – as an instigator of health problems, including the development and progression of cancer (Allen et al. 1997) or immunosuppression (Blakley et al.1999; Luebke 2002) in humans, as well as increased health risks for pesticide applicators after occupational exposure (Cattani et al. 2001) and people living in homes that had been previously treated with organochlorine insecticides (Dingle et al. 1999). The environmental persistence of these early insecticides has been widely noted and the bulk of the data focuses on insecticides that have largely been removed from the market (organophosphates, organochlorines and carbamates). Encouragingly, many novel insecticides and biopesticides are highly specific for insects, degrade quickly into their non-toxic components (or, require activation by insect enzymes to become toxic), and can be used readily with biocontrol or IPM programmes (Hall and Menn 1999). Isolated components of spider venoms known to act almost exclusively on insects and other arthropods have low oral vertebrate toxicity and are promising candidates for target-specific insecticide discovery programmes (Wang et al. 1999; Tedford et al. 2004).

The pyrethroids, neonicoinoids and insect growth regulators (IGRs) are now the most widely used insecticides developed in the last two decades. Nauen and Bretschneider (2002) provide an excellent overview of the mechanisms of action of these and other novel insecticides. Pyrethroids and neonicotinoids are appealing because of the low dose needed for lethality in insects, low mammalian toxicity at suggested application rates, biochemical stability, low environmental persistence, readily biodegradable nature and repellent properties (Tomizawa et al. 2000); the stability and activity of native compounds can be further improved in synthetic formulations by modifying side chains, or adding sunscreens and synergists. Due to their unique mode of action as agonists of the insect central nervous system, cross-resistance with other insecticides is limited or absent, although resistance has been noted previously (Nauen and Denholm 2005). Synthetic pyrethroids have low mammalian toxicity and the non-target organisms likely to be affected during label-approved use are primarily fish and other invertebrates (Tomizawa and Casida 2005). These concerns and others about possible effects on beneficial insects can be eased by changing the method of delivery and time of day the insecticide is applied (Dent 2000). The flexible nature of these novel comounds and reduced-risk characteristics make them exceptionally good candidates for use in sensitive environments, including indoors and to protect food and grain stores.

IGRs are highly specific compounds that interfere with insect development at embryonic, larval and nymphal stages. Insects and arthropods are the sole targets and the possibility exists for many of the hormone analogues to be species-specific (Dhadialla et al. 1998). Among these IGRs are juvenile hormones, chitin synthesis inhibitors and triazine derivatives. The moulting hormones (ecdysones) and juvenile hormones are both involved in the control of larval and nymphal metamorophosis, specifically during moulting, making the timing of the application critical for any significant population decline to be observed. Triazine derivatives, like the substituted melamine cryomazine, appear symptomatically similar to IGRs, causing death due to cuticular lesions. However, these compounds do not act directly on chitin synthesis as do the true IGRs, and the mutation of several genes may be needed to explain the development of resistance (McKenzie and Batterham 1998).

Monitoring-bait systems using IGRs have proved especially effective for the prevention and management of subterranean termite infestations, including the economically important Formosan subterranean termite *C. formosanus* (Su and Scheffrahn 1998). Once termites actively attack these stations the previously untreated lumber bait is replaced with timber laced with a slow-acting insecticide; commonly used compounds are chitin synthesis inhibitors (e.g. hexaflumuron) or metabolic inhibitors (e.g. sulphluramid, hyrdamethlynon). Su and Scheffrahn (1998, 2000) review the economic impact of pestiferous termites and detail currently available treatments compatible with IPM programmes and other prevention measures in depth.

## Examples of success

Three case studies follow to translate this information into an applied strategy for invasive social insects: fire ant eradication in Australia and the Galapagos Islands and wasp management in New Zealand.

Recently there have been two eradication programmes in Australia that have met the criteria Myers et al. (2000) established for successful eradication. The six criteria are first: sufficient funding to undertake a large-scale project; second, that authority must be granted to an agency to allow for the development and maintenance of regulations, treatments and monitoring; third, for the biology of the invasive animal to be known and specifically for its susceptibility to control measures to be assessed; fourth, to prevent reinvasion; fifth, to monitor the pest at low densities; and finally, for restoration and continued management of the invaded environment, particularly if the invader has become a 'keystone' species in the habitat.

The Australian programmes have been focused on the Tropical Fire Ant (*Solenopsis geminata* (Fabricius)) in suburban Brisbane, Queensland (Vanderwoude et al. 2003), and *S. geminata* and the Coastal Brown Ant (*Pheidole megacephala* (Fabricius)) in Kakadu National Park, Northern Territory, a World Heritage site (Hoffmann and O'Connor 2004). Hoffmann and O'Connor used a three-phase approach: scoping, to establish population distribution(s) and set cost and time parameters; treatment, when hydramethylnon was applied; and finally, post-treatment monitoring. Hydramethylnon (a trifluoromethyl aminodydrazone compound that inhibits electron transport), which rapidly degrades into non-toxic compounds when exposed to ultraviolet light and has low terrestrial vertebrate toxicity, was a safe and effective choice for a conservation area like Kakadu. The 2-year post-treatment monitoring period was split into a first 12-month intensive monitoring phase, at which point follow-up applications were made (in the case of persistent infestations, with the organophosphate diazinon) and a second 12-month continuation of the monitoring phase. In the case of the diazinon-treated colonies, their two-year monitoring period began again after the treatment, and the other colonies appeared eliminated after the first round of treatment.

Alien insect introductions to the Galapagos Islands are estimated to have increased to 463 species in 2006 from 277 in 1998 (Causton et al. 2006). Due to the high percentage of herbivorous invaders, in the Galapagos the endemic flora face the highest threat from invasive insects. The Little Fire Ant, *Wasmannia auropunctata* (Roger), has colonized eight large islands in the Galapagos Islands since its introduction and subsequent spread for the past 35–70 years. Causton et al. (2005) developed an eradication plan for Marchena Island based on repeated applications of hydramethylnon along a series of close linear transects; surveys 9 months after treatment showed two small populations remaining in approximately 0.1% of the originally infested area, and continued monitoring suggests that the rapid drop in population may be permanent and the ant population will continue to be suppressed with continued treatment. Causton et al. (2006) reported the continued presence of *W. auropunctata* as well as *S. geminata* in the Islands; subsequent eradication programmes similar to the successful one outlined were implemented.

Both European (*Vespula germanica* (Fabricius)) and English (*Vespula vulgaris* (Linnaeus)) (Hymenoptera: Vespidae) wasps can be found throughout New Zealand preying heavily on native biota, especially insects and other arthropods. Clapperton et al. (1994) found that between 1987 and 1990 *V. vulgaris* had increased its distribution and almost completely


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displaced *V. germanica* in honeydew beech forests (beech forests infested with scale insects) and rural habitats, but *V. germanica* maintained populations in urban areas and native forest. Both species were widespread in 1990 and the distribution pattern changes affected the species composition, but not overall wasp density, on both the North and South Islands. Beggs et al. (1998) found no differences in the efficacy of baiting traps for wasps with either sulfuramid (a phenylpyrazole) or sodium monofluro-acetate (1080, which disrupts the citric acid cycle) in honeydew beech forest. Later, Harris and Etheridge (2001) found fipronil (a phyenylpyrazole) acted faster at lower doses than sulfuramid when used as in bait for *Vespula* spp. in similar habitat, reducing colony presence in the treated area by over 99%. Although complete eradication of invasive vespids is unlikely for New Zealand, the use of fipronil bait stations may help minimize populations in areas with high populations of at-risk native prey items.

## Discussion

With the increased specificity of newer insecticides trials using several insecticides with different modes of action and delivery mechanisms can provide a multi-pronged approach to intractable invasive insect pests. Island ecosystems, in particular, are sensitive to the environmental repercussions of wide-scale insecticide use and care must be taken to minimize non-target impacts – especially where native and endemic invertebrates are concerned. Island geography may offer certain challenges to the spread of invasive species because of the potential for drastic habitat changes in a small area, for example in temperature and altitude, granting a temporary reprieve from continued invasion and providing advantages that can be used to develop and tailor management strategies.

The case studies mentioned in this review utilized different chemical strategies, which speaks to the advantages of having insecticides available with diverse mechanisms of action, but there were also some basic aspects that were similar. In particular, in all three successful strategies an initial survey was conducted to determine the reach of the infestation; a programme was put in place to bait, trap and treat the infestation; and finally, post-treatment monitoring was performed, and subsequent applications were made and monitoring extended if the infestation was persistent. Programmes like these can serve as models to other sensitive environments, not just islands, and can provide a baseline for many low-impact eradication plans once an invader has been introduced.

Although prevention continues to be an important first line of defence against invasive organisms for islands, new chemical control options are becoming increasingly viable as the specificity of the insecticides increase and non-target impacts are minimized. Modern insecticides that are highly specific to insects, and sometimes act only on individual species (e.g. hormone analogues), are becoming a valuable part of effective IPM strategies. The creation of individual, specialized risk assessments for island and other sensitive ecosystems helps to prioritize which invasive insects pose the greatest risk to native flora, fauna, or both (Causton et al. 2006). The challenge of moving past the legacy of broad-spectrum, environmentally persistent insecticides is a formidable one, but the payoff – and possibilities for eradication – require action, public education, and continued research efforts.

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