ANNUAL REVIEWS

*Annual Review of Entomology*

# Exotic Ants of the Asia-Pacific: Invasion, National Response, and Ongoing Needs

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Annu. Rev. Entomol. 2022. 67:27–42

First published as a Review in Advance on September 28, 2021

The *Annual Review of Entomology* is online at ento.annualreviews.org

https://doi.org/10.1146/annurev-ento-060721-085603



## Keywords

invasive species, fire ants, economic importance, dispersal modes

## Abstract

Human activity has facilitated the introduction of many exotic species via global trade. Asia-Pacific countries comprise one of the most economically and trade-active regions in the world, which makes it an area that is highly vulnerable to invasive species, including ants. There are currently over 60 exotic ant species in the Asia-Pacific, with the red imported fire ant, *Solenopsis invicta*, among the most destructive. Exotic ants pose many economic and ecological problems for the region. Countries in the Asia-Pacific have dealt with the problem of exotic ants in very different ways, and there has been an overall lack of preparedness. To improve the management of risks associated with invasive ants, we recommend that countries take action across the biosecurity spectrum, spanning prevention, containment, and quarantine. The creation of an Asia-Pacific network for management of invasive ants should help prevent their introduction and mitigate their impacts.

## INTRODUCTION

Globalization and human trade and transportation are breaking down biogeographic barriers, and many plant and animal species are being transported to new areas (10, 15). Ants are dominant terrestrial insects in ecosystems and among the most studied insect groups (28, 63). Before intervention by humans, ants were comparatively poor dispersers across continents. However, they have been introduced by human trade and travel from their native regions to different corners of the world (36, 66). Organisms that have completed the first step (i.e., initial dispersal) of the introduction process are usually considered to be exotic species (38). Exotic ants, sometimes called tramp ants, are species that are inadvertently transported with cargo on ships, trains, etc., by human trade due to their small size, general nesting habits, and opportunistic diets, and they have the potential to become some of the worst invasive species worldwide. Exotic ants become invasive species if they have the potential to spread in their introduced ranges; become ecologically dominant; and adversely affect ecosystems, biodiversity, urban environments, and human health (50). Loss of intraspecific aggression and supercolony formation characterize many invasive ants and are considered to be key factors driving their invasion success (1, 34).

Different biogeographic regions have varying numbers of introduced species due to climate matching, shipping frequency, and routes of trade. Moreover, biotic resistance together with anthropogenic disturbance may limit ant competitive success and distribution in new habitats; 14 out of the 19 most destructive invasive ant species have invaded Asia-Pacific countries. Since the discovery of the red imported fire ant (RIFA), *Solenopsis invicta*, in mainland China in 2004, this species has spread to more than 10 provinces and regions. Fire ants have recently been intercepted at ports of entry in Japan and South Korea. Oceanic islands with no native ant fauna have received the greatest number of introduced ant species. Australia also hosts several ant invasions, while the Indo-Malay regions have records of invaders equal to those of Australia. Many exotic ants have become highly destructive and invasive in different areas of the Asia-Pacific region.

Asia-Pacific countries, which comprise 38% of the world's population, 60% of the world's GDP, and 47% of the world's trade, are expected to grow rapidly in population size and trade volume in the coming years. Identification of donor regions of exotic ants to the Asia-Pacific is critical for effective management of ant invasions. Careful observations of shipping routes and consignments from regions with the highest probability of introduction are essential to prevent ant entry and for proactive management. In this review, we call attention to the most significant exotic ants in Australia, China, New Zealand, and other parts of the Asia-Pacific, including Pacific Island countries and territories (PICTs), where they have become established. The pathways of movement to these countries, coordinated approaches taken by these countries to prevent the introduction of exotic ants, and how to deal with existing infestations, along with future needs, are discussed. The successes of some countries, e.g., New Zealand, could form a blueprint for other countries to prevent the introduction of invasive ants.

## ECONOMIC IMPORTANCE OF EXOTIC ANTS IN ASIA-PACIFIC COUNTRIES

Many exotic ant species are likely to cause significant economic losses after their successful invasion. The economic impact of exotic ants mainly involves (*a*) agriculture, (*b*) property and electrical equipment, and (*c*) cost of control. The main species of concern are *Anoplolepis gracilipes*, *Linepithema humile*, *Pheidole megacephala*, *Solenopsis geminata*, *S. invicta*, and *Wasmannia auropunctata*. For example, the total yearly economic damage caused by the RIFA, *S. invicta*, in the United States, where it was introduced in the 1930s from Argentina, not counting environmental problems, which are especially difficult to enumerate, has been estimated at US$5–6 billion (42, 57).

Gutrich et al. (27) discussed the potential impact if the RIFA were to invade Hawaii. They estimated the cost over 20 years to be US$2.5 billion, or 0.17% of GDP (9). Potential annual cost impacts of the RIFA in Australia if the pest were to become widespread are estimated at AU$1.65 billion (96). Aoyama et al. (2) also estimated up to 43 billion JPY in damage would result if the RIFA were to invade Okinawa. If other countries in Asia were to be invaded by the RIFA (93), their annual costs based on a similar proportion (0.17%) of GDP in 2019 would be more than US$50 billion, including approximately US$25 billion for China, US$9 billion for Japan, US$5 billion for India, US$3 billion for the Republic of Korea, US$2 billion for Indonesia, and US$1 billion for Thailand. While *S. invicta* is among the most destructive invasive ants, the damage by other species is also costly.



## Agriculture

Exotic ants can be important agricultural pests, impacting plants and cropping systems by damaging roots, seedlings, sprouts, flowers, and seeds; preying on flower-visiting insects; and tending aphids and other honeydew-producing insects (12, 35, 52, 94). The presence of the RIFA decreases flower number, pod number, and yield of mung beans in China (94). In the Pacific, *P. megacephala* is particularly noted as a pest of sugarcane and pineapple through its tending of mealybugs (20), which not only damage the plant directly but can vector plant diseases such as pink pineapple mealybug wilt (62). In Hawaii, *A. gracilipes* can damage banana fruit with its abdominal secretions (54).

Some exotic ants, especially the RIFA, not only bite or sting people, but also hurt pets, domestic animals, and wild animals. Newly hatched chickens may be killed by the RIFA if stung and injured. Newborn cattle and other livestock are occasionally injured or killed if birth occurs too near a RIFA nest (69).

## Property and Electrical Equipment

A second major problem is damage to electrical equipment (76). The destroyer ant, *Trichomyrmex destructor* (formerly called *Monomorium destructor*), and the RIFA chew wires, causing electrical shorts (76, 86). *Solenopsis invicta* can build their earthen mounds inside warm electrical equipment, causing problems with transformer boxes, street signal boxes, airport landing lights, well pumps, and virtually any other electrical equipment set on or in the ground (76). In Texas in the early 2000s, almost US$150 million (0.015% of GDP) was spent annually on repair and replacement of electrical and communication equipment (42); this would equate to some US$30 billion in Asia at a similar proportion of GDP (93).

## Environmental Impact of Exotic Ants

Ants are major predators in most terrestrial ecosystems, where they significantly impact biological communities, especially arthropods (21). Introduced populations of the RIFA and Argentine ants are well documented to reduce the diversity of native arthropods. In Hawaii, where there are no native ants, invasive ant species have had major impacts on native fauna, including vertebrates, plants, and arthropods (39). Given the endemic nature of many Pacific Island species, invasive ants are of particular concern for species conservation efforts.

One of the best-documented examples of invasive ant effects is that of *A. gracilipes* on Christmas Island, an Australian territory close to Indonesia, where the ant has caused an invasional meltdown in the rainforest ecosystem of the island (56). In invaded areas, the ants extirpate a keystone species, the endemic red land crab, *Gecarcoidea natalis*, the dominant consumer on the forest floor. In doing so, the ants indirectly release seedling recruitment, enhance species richness of seedlings, and slow litter breakdown. In the forest canopy, associations between *A. gracilipes* and sap-sucking scale insects lead to high population densities of the scales, growth of sooty molds, and canopy dieback or tree death. These combined effects have transformed the island's rainforest ecosystem.

### Cost of Controlling Exotic Ants

The cost associated with the control of exotic ants is significant. An eradication program is usually adopted when the introduced ants are first detected and before they become widely distributed. Successful eradication of an invasive ant has rarely been achieved. The amount of insecticide and labor required for frequent monitoring and application can be quite high, making the cost of eradicating exotic ants several times that of conventional control. To date, New Zealand is the only country to have successfully eradicated the RIFA and has spent over US$6.1 million since 2001 responding to three RIFA incursions (27). Australia is currently the only country making a serious attempt at eradicating a large population of RIFAs over an area in excess of 400 $km^2$. As of 2016, a total of AU$330 million had been expended on the program over a 15-year period, and in 2017, a further AU$411 million was committed for an additional 10 years (98). However, regular ongoing expenditures are needed to limit the spread and damage of exotic ants after they become widely distributed. The overall estimated annual cost from 2018 to 2020 to all infested provinces in China for RIFA control was over US$30 million (19).

## DISPERSAL MODES OF EXOTIC ANTS IN ASIA-PACIFIC COUNTRIES

### Invasion Routes

The most likely modes of introduction into new countries are via sea cargo and by air. At least 114 ant species were recorded entering New Zealand from 1955 to 2005 (83), and 232 were recorded entering the United States over a 60-year period (66). In New Zealand, the biggest entry routes during a period of intensive study were sea cargo (43%) and air passengers (34%), followed by air cargo (16%) and mail (5%) (83). RIFAs have been discovered several times in New Zealand (6). In China, exotic ants have been intercepted increasingly frequently at ports in Guangdong during recent years (49, 99).

Introduced populations of exotic ants often become the sources of new invasions, a phenomenon known as the bridgehead effect (5). In fact, the main source of the RIFA in the Asia-Pacific region has been the United States (3), rather than the species' native range in South America. Unfortunately, in Asia, the number and proximity of potential source countries continue to grow. The RIFA is well established in mainland China (100), Hong Kong (92), and Taiwan (11), and these regions are now likely to become sources of further introductions.

### Establishment and Spread

Successful establishment of exotic ants requires the introduction of either entire colonies or inseminated queens that then found new colonies. Exotic ants are usually introduced to new regions by transportation of plant material like turf and potted nursery stock (32, 53, 65). RIFA-infested nursery stock was a major source of distribution in the United States and China (79, 98).

The most likely carriers of exotic ants are objects with moist soil. Potted plants, soil on construction vehicles, and shipping containers left sitting on the ground are all possible carriers. Hay bales and logs stored on the ground before transport are also known to carry ant colonies. Newly mated queens would most likely be transported in items of air cargo that had been left sitting out on the ground. The ability of colonies and/or inseminated queens to become successfully established depends on the availability of suitable nesting sites (66) in the introduced area.

Environmental factors, especially temperature and moisture, play key roles in determining the distribution of ant species as well as biotic resistance of native communities (59, 82). A model by Morrison et al. (53) predicts that *S. invicta* can survive in nearly all parts of Asia-Pacific countries except for high-altitude areas and arid regions. Once established in an area, spread occurs through both human-mediated jump dispersal and mating flights (65).

Research on the global invasion history of the tropical fire ant suggests a corresponding spread of *S. geminata* from Mexico via Manila to Taiwan, and from there throughout the Asia-Pacific countries (22). *Linepithema humile* has been introduced to many temperate, tropical, and subtropical regions in the Asia-Pacific, although its distribution is somewhat patchy (91). We can expect this species to continue to spread in the region, especially in parts of southern China that have appropriate Mediterranean-like climates, where this exotic ant would be expected to have a great impact (91).



## EXOTIC ANT SPECIES IN ASIA-PACIFIC COUNTRIES

### Mainland China and Taiwan

China has the fourth-largest land area in the world and possesses an extraordinary diversity of habitats and climatic conditions that favor development and survival of many insect species, including ants (101). Guenard & Dunn (26) identified 15 exotic ant species in mainland China, the majority coming from neighboring Asian countries. These species include *A. gracilipes*, *Monomorium floricola*, *Paratrechina longicornis*, *P. megacephala*, *S. geminata*, *S. invicta*, *Tapinoma melanocephalum*, and *Technomyrmex albipes* (33, 63, 77) (**Table 1**).

More than 20 introduced ant species have been reported in Taiwan, including most of the species mentioned above for mainland China (70). Arboreal or wood-dwelling ants are frequently intercepted and may produce the next wave of ant invasions in Taiwan (43).

### Australia

There are currently 38 species of exotic ants known to be established in Australia, including six of the world's most destructive invasive ants, e.g., *A. gracilipes*, *L. humile*, *P. megacephala*, *S. geminata*, *S. invicta*, and *W. auropunctata* (33). These six species are at various stages in the invasion process, with more than 100 years separating the earliest and latest arrivals.

### New Zealand

Of the 28 species of exotic ants established in New Zealand, only *L. humile*, *Monomorium pharaonis*, and *P. megacephala* are currently listed by government authorities as being of major importance (81), although more for their potential than for their actual impacts.

### South Korea

South Korea has relatively few invasive ants, although several species are routinely intercepted at ports. *Tapinoma melanocephalum* has been a pest in South Korea, where it can live outdoors in the summer and indoors the rest of the year, since at least 2005 (46). *Solenopsis invicta* is frequently intercepted at quarantine points; the first established colony of *S. invicta* was found at Gamman Port in Busan in September 2017 (98). Since then, colonies have been found at container terminals in several ports and at an inland construction site. They continue to be found in containers primarily arriving from China. In 2019, infestations of the Argentine ant *L. humile* were found in container yards in the ports of Busan and Kwangyang (44). The status of these infestations is not currently known.

**Table 1 List of main exotic ant species established in Asia-Pacific countries based on abundance, distribution, and impacts**

| Genus and species | Common name | Origin and native range | Distribution in the Asia-Pacific | Reported socio-economic or environmental impacts | Selected references |
|---|---|---|---|---|---|
| **Dolichoderinae** | | | | | |
| *Linepithema humile* (Mayr) | Argentine ant | Argentina, Brazil | Australia, New Zealand, Vanuatu, Hawaii, Japan, South Korea, Indonesia, Philippines, Malaysia, Vietnam | Major | 14, 16, 86 |
| *Ochetellus* sp. (*glaber* group) (Mayr) | Black household ant | Australia | New Zealand, Solomon Islands, Hawaii, China, Japan, Borneo, Philippines | Minor to moderate | 16 |
| *Tapinoma melanocephalum* (Fabricius) | Ghost ant | Indo-Malay | Australia, all PICTs, China, Japan, South Korea, Southeast Asian countries | Major | 24, 46, 68, 87 |
| *Technomyrmex albipes* (Smith) | White-footed house ant | Indo-Pacific | Australia; all PICTs except American Samoa, Kiribati, Northern Mariana Islands, Tuvalu, and Vanuatu; Hawaii; China; Korea; Cambodia; Laos; Vietnam; Philippines; Malaysia | Major | 24, 51, 68 |
| **Formicinae** | | | | | |
| *Anoplolepis gracilipes* (F. Smith) | Yellow crazy ant | Indo-Malay | Australia, all PICTs, Hawaii, China, Japan, Southeast Asian countries | Minor to massive | 24, 68, 84 |
| *Paratrechina longicornis* (Latrielle) | Black crazy ant | Indo-Malay | Australia, all PICTs, Hawaii, China, Japan, Southeast Asian countries | Moderate to massive | 24, 68, 85 |
| **Myrmicinae** | | | | | |
| *Monomorium floricola* (Jerdon) | Bicolored trailing ant | Indo-Malay | Australia, all PICTs except Tuvalu, China, Japan, Southeast Asian countries | Moderate to massive | 24, 68, 71, 88 |
| *Monomorium pharaonis* (L.) | Pharaoh's ant | Indo-Malay, Africa, India | Australia; New Zealand; all PICTs except Cook Islands, Niue, Tuvalu, and Wallis & Futuna; China; Japan | Moderate to major | 16, 24, 68, 71 |
| *Pheidole megacephala* (Fabricius) | African big-headed ant | Afrotropic | Australia, New Zealand, all PICTs except Nauru, Hawaii, China, Japan | Minor to massive | 16, 24, 39, 68, 71 |
| *Solenopsis geminata* (Fabricius) | Tropical fire ant | Neotropic | Australia; all PICTs except Niue, Tokelau, and Wallis & Futuna; Hawaii; China; Japan; Southeast Asian countries | Moderate to massive | 24, 31, 71, 89 |
| *Solenopsis invicta* Buren | Red imported fire ant | Neotropic | Australia, China, Japan, South Korea | Massive | 74, 98 |
| *Tetramorium bicarinatum* (Nylander) | Bicolored pennant ant | Indo-Malay | Australia, New Zealand, all PICTs, China, Japan | Minor to massive | 16, 24, 68, 71 |
| *Tetramorium simillimum* (F. Smith) | NA | Afrotropic | Australia, all PICTs except Nauru, China, Japan | Minor | 24, 68, 71 |
| *Trichomyrmex destructor* (Jerdon) | Singapore ant | Palearctic | Australia; all PICTs except New Caledonia, Tokelau, Tonga, Vanuatu, and Wallis & Futuna; China; Japan; Southeast Asian countries | Moderate | 24, 68, 71 |
| *Wasmannia auropunctata* (Roger) | Electric ant, little fire ant | Neotropic | Australia, American Samoa, French Polynesia, Guam, Federated States of Micronesia, New Caledonia, Papua New Guinea, Solomon Islands, Vanuatu, Wallis & Futuna, Hawaii | Massive | 24, 90 |

Abbreviations: NA, not applicable; PICTs, Pacific Island countries and territories.

The tropical fire ant, *S. geminata*, was first intercepted in the Port of Busan in 1999 in a shipment from Myanmar and has been detected in 10 other shipments arriving from seven other countries up to 2006 (45).

## Japan

In Japan, 41 exotic ant species have reportedly established populations (71). The Argentine ant was discovered in 1993 and is now reported in 11 prefectures. Mitochondrial haplotype analysis detected the presence of five supercolonies that possibly originated from independent incursions (37). Since the first detection of *S. invicta* in 2017, there have been 78 subsequent interceptions of this pest up to September 2021. Although they were not reported in the recent review by Wylie et al. (98), five relatively mature wild colonies were found during 2019–2020 in Tokyo, Yokohama, and Nagoya. All nests were found in cracks in the pavement of the harbor or roadside soils. *Lepisiota frauenfeldi* was discovered to have established wild populations in Japan in 2017 and is currently found in six prefectures.

While the following ants are not officially regarded as pests in Japan, their potential invasiveness has been recognized. By the 1970s, *P. megacephala* was widely established in the Ryukyu Islands, its distribution being limited to open lands such as beachside and urban parks. However, there is now concern about a recent invasion in the Ogasawara Islands, where the ant is invading forests and damaging the diversity of land snails (72). In Yanbaru National Park on Okinawa, 89% of the honeydew-producing insect colonies on roadsides are occupied by three exotic species, *P. megacephala*, *A. gracilipes*, and *Technomyrmex brunneus* (67).



### Southeast Asia

*Anoplolepis gracilipes*, *T. destructor*, *M. floricola*, *P. longicornis*, *S. geminata*, and *T. melanocephalum* are all widely distributed in Southeast Asian countries, and there are also records of *L. humile* from this region (**Table 1**).

Although the occurrence of *S. invicta* has not been confirmed in Southeast Asia, several countries in this region, such as Myanmar, Laos, and Vietnam, border known populations of the pest in China and are therefore at risk. There are few active myrmecologists monitoring for invasive ants in this region, so it is certainly possible that there are undetected populations, as is also the case in other Asia-Pacific countries like Indonesia, Malaysia, Papua New Guinea, and the Philippines. Singapore, a transport hub for international trade, is also likely to be invaded by this ant (98).

### Pacific Island Countries and Territories

Of the ant species recorded in the PICTs, 44 are considered to be invasive (61), and several of these are among the most important in the Asia-Pacific region (**Table 1**). Considerable information about these species is available from the Pacific Invasive Ant Distribution database, part of the Pacific Invasive Ant Toolkit (24).

### Hawaii

Some 45 ant species have become established in Hawaii, which has no native ants, over the past two centuries (39). Smith (64) provided the first description of ants in Hawaii. These species likely arrived with the colonization of Hawaii by the Polynesians and the later visits to Hawaii by European traders (58). In 1879, *P. megacephala* and *S. geminata* were already established (64). In addition to these two species, most major pest ant species are present, including *L. humile*, *A. gracilipes*, *W. auropunctata*, and *P. longicornis*.

## NATIONAL RESPONSES TO EXOTIC ANTS IN ASIA-PACIFIC COUNTRIES

The responses of Asia-Pacific countries to incursions of exotic ant species have varied considerably, reflecting different levels of preparedness, capacity to respond, and country priorities. Other influencing factors may include geography (whether an island nation or sharing land borders with other countries), climate, and the nature of the ant invader itself. Reported incursion responses and outcomes in different countries are summarized below.

## Mainland China and Taiwan

Following the discovery of *S. invicta* in Wuchuan in 2004, the Ministry of Agriculture initiated an eight-year eradication program in 2005, details of which are provided by Zhang et al. (100). Complete eradication was anticipated by 2013. Every provincial government established research institutions and specific organizations to manage the pest, and the Chinese government provided special funds for control. To date, seven successful eradications of isolated populations of *S. invicta* have been officially announced. In spite of this, the RIFA has rapidly spread and continues to expand in China, and in 2015, the infestation spanned over 1 million ha (78). Apart from *S. invicta*, other invasive ants are almost completely ignored, but this is expected to change with the promulgation of the Biosecurity Law of the People's Republic of China (effective from April 15, 2021).

In Taiwan, following the discovery of *S. invicta* in Taoyuan City in 2003, the National Red Imported Fire Ant Control Centre was established in 2004 to develop control strategies and provide technical support. However, the on-the-ground implementation of the program was devolved to a consortium of national and local government members, each with their own budget and eradication program. The successful eradication of the Chiayi population of *S. invicta* was officially announced in 2017 (98). Despite this, *S. invicta* has continued to spread in Taiwan, and at the end of 2020, 10 cities were confirmed to be infested by the ant.

## South Korea

Following the detection of *S. invicta* at Busan's Gamman Port in 2017, the Ministry of Agriculture, Food and Rural Affairs and the Animal and Plant Quarantine Agency launched an aggressive campaign to eliminate any colonies found and to inspect for the presence of colonies at ports. An intensive monitoring and inspection effort found additional infestations at three ports, and in 2018, the ant was found at the inland city of Daegu (98). All infestations were treated on detection.

## Australia, Including Christmas Island

Australia, as an island continent, has long had a strict approach to border quarantine, particularly since the 1950s (95), and has a strong record of responses to incursions of exotic species including ants. An early example of the country's commitment to a long-term ant eradication program is the effort to eradicate the Argentine ant from Western Australia over the period 1954–1988 (73). The program was canceled in 1988 following a review of the program's use of heptachlor by the Environmental Protection Authority, and the ant is now widespread in southern states.

There have been eight separate incursions of *S. invicta* into Australia since the first discovery of this species in Brisbane in 2001. Of these, six have been eradicated, including a genetically distinct population at the Port of Brisbane (8,300 ha), which is the largest recorded eradication of any ant species worldwide (30). Wylie et al. (97) described the techniques that were used to eradicate these incursions. In 2017, an additional AU$411 million was committed for a new 10-year program to eradicate the remaining Brisbane population (with an approximately 500,000-ha footprint), and eradication is also underway for a recent small incursion of the ant in Western Australia.

At Christmas Island, helibaiting operations targeting supercolonies of *A. gracilipes* were conducted in 2002 and 2009 (7). Ant activity was reduced by 99.4% 20 weeks after baiting, with minimal nontarget impacts. Currently, biological control efforts are underway to reduce scale insect densities, which could reduce carbohydrate supply to the ants and in turn lead to the decline of supercolonies (55). In Queensland and the Northern Territory, localized eradication programs for *A. gracilipes* were implemented (29, 41), and some discrete infestations have been eradicated (29).

Another long-running eradication program is that of *W. auropunctata* in northern Queensland, which commenced following discovery of the ant in Cairns in 2006. The program is currently on track to eradicate the remaining areas of ant population by July 2021. Other ongoing eradication programs for exotic ants in Australia include those for *L. frauenfeldi* in the Northern Territory, Western Australia, and Queensland and for *Lepisiota incisa* in Western Australia. Successful localized eradication has been achieved for *P. megacephala* and *S. geminata* in the Northern Territory (31).

## New Zealand

Prior to 2001, few eradication attempts had been made on various tramp ant species discovered nesting around ports (47). Some of the reasons for this are historical: 19 of the 26 exotic ant species established in New Zealand were first recorded more than 60 years ago, when the response to incursions was more likely to be management rather than eradication. In justification of this response, the impact of most introduced species in New Zealand has been minimal, and many tramp ant species are regarded as ephemeral, mainly in consideration of climate limitations (47). This approach changed in 2001 with the discovery of *S. invicta* at Auckland International Airport and, later, separate incursions of this ant at the port of Napier in 2004 and 2006 (13). Eradication programs implemented for all three incursions were successful. Since 2003, postborder detections of *P. longicornis*, *S. geminata*, *A. gracilipes*, and *T. destructor* have also been eradicated (4). Eradication of *L. humile* from 11 ha on Tiritiri Matangi Island, a scientific reserve near Auckland, was declared in 2016 following a treatment program that commenced in 2001 (23).

## Japan

Several exotic ants (*Solenopsis* fire ants of Central and South American origin; *L. humile*; *L. frauenfeldi*; and *W. auropunctata*, which has yet to invade) are official targets of control by Japanese law. A population of Argentine ants in Ota Ward, Tokyo, spanning an area of 24.5 ha, was successfully eradicated after a three-year application of paste-baits containing fipronil and injection of the liquid into nests (60). Because fipronil is highly persistent in soil, the paste-baits were applied using bait stations, instead of scattering them directly on the ground surface. The discovery of the RIFA in 2017 triggered regular distribution surveys twice a year at more than 60 major sea ports. *Solenopsis geminata* and *L. frauenfeldi* were intercepted as a byproduct of this port survey. Extermination of wild colonies of the RIFA and wild populations of *L. frauenfeldi* is still under way.

## Pacific Island Countries and Territories

While invasive ant species such as *A. gracilipes*, *P. megacephala*, and *W. auropunctata* are recognized as a biosecurity priority in many PICTs and are included in their preparedness or action plans, there have been few attempts to eradicate incursions or manage those species already established. Vergnes & Jourdan (75) detail an attempt in New Caledonia to eradicate *W. auropunctata* from a 9-ha invaded area in a forest remnant near Noumea using an insect growth regulator followed by a toxicant. They recorded a significant decrease in the population of the ant, but relictual nests remained. Case studies of other attempted eradication or control efforts, which have been largely unsuccessful, are listed in the Pacific Invasive Ant Toolkit (24).

## Hawaii

In 1999, the Hawaii Ant Group, an informal interagency collaboration, was established to provide technical support to the Hawaii Department of Agriculture (HDOA) for the containment and eradication of *W. auropunctata* and to prevent the establishment of *S. invicta* (39).

*Solenopsis invicta* was first intercepted by the HDOA inspectors in 1991, and in 2001, the US Department of Agriculture assisted the Hawaii Ant Group and the HDOA to develop a Red Imported Fire Ant Prevention Plan. While the plan was completed in October 2001, the link to the website and to the Hawaii Ant Group is no longer active. *Wasmannia auropunctata* is largely confined to the main island of Hawaii, with one infestation on the island of Kauai. In 1999, the HDOA enacted quarantine regulations to prevent the spread of potted plants infested with *W. auropunctata* from the island of Hawaii to other islands. At a 2004 meeting of the Pacific Plant Protection Organization held in Fiji, the Pacific Invasive Ant Prevention Plan (PIAPP) was presented and endorsed by 21 Pacific island countries. As of 2005, the Invasive Species Specialist Group was trying to obtain funding for this plan (39), and there is no evidence that any plan was effectively implemented.

## Lessons from National Responses

Several common themes can be elicited from the manner of spread of exotic ants in the Asia-Pacific and the national responses to invasions.

First, except for a few countries and a few select ant species, there is a general lack of awareness across the region of potential impacts of invasive ants, which has contributed to a lack of preparedness to deal with such threats. For example, even the well-known *S. invicta* was not on China's watch list of invasives prior to its detection in that country (48), and in Taiwan, the ant was not declared a quarantine pest until 11 months after its first detection (40). In Australia, it was not until the discovery of *S. invicta* in 2001, 10 years after it is believed to have arrived, that the threat posed by exotic invasive ants began to be fully realized, prompting a raft of initiatives to deal with the issue.

Second, while it is generally accepted that the earlier an exotic organism is detected, the better is the chance of eradication, few countries have effective systems in place for early detection and monitoring for invasive ants. This is particularly the case for many PICTs, where, for example, *W. auropunctata* continues to spread despite being identified by these countries as a priority species (25).

Third, the importance of a single agency to coordinate national monitoring and response efforts cannot be overemphasized. For instance, in some countries, prevention and control measures against *S. invicta* have been implemented by different agencies, each with their own area of responsibility and with varying levels of efficacy. A lack of coordination in the timing of treatment applications in different areas can lead to treatment failure (98).

Fourth, resourcing is obviously a major issue for developing countries in the region. As with the example of the PIAPP, good intentions do not necessarily translate into desired outcomes without firm funding and resource commitments from more affluent regional partner countries.

## Recommendations to Management Authorities

Based on these lessons, an overarching recommendation is that each country develop an action plan to deal with invasive ants. Ideally, the plan would encompass a national approach across the entire biosecurity continuum—prevention, detection, response, containment, and asset-based protection or ongoing management—and set out specific actions and priorities to improve the management of risk associated with invasive ants (18).

Among the preventative measures that could be undertaken, an important first step is to make a comprehensive assessment of the risks posed by invasive ant species and the mechanisms behind their arrival and establishment. This assists in decision making by allowing biosecurity authorities to prioritize and target risks (80). Risk assessments can also be used to assess the threats of already established and widespread invasive species. Offshore initiatives could include engaging with trading partners to institute measures to reduce the risks of accidental transport of invasive ants on cargo and containers at ports of departure. In this context, there is growing support for international shipping container phytosanitary standards.

Early detection programs are essential to finding exotic invasive ants as soon as possible after they have entered a country, while populations are still small enough to be eradicated or at least aggressively contained. A key element is the development of diagnostic tools to differentiate between exotic and native ants, including genetic analysis to determine the origin of the infestation and whether any spread relates to a current or new incursion (97). Related to this is the need to develop national reference collections and for training of diagnosticians. Regular surveys around seaports and international airports will enhance early detection of any invasive ant incursions, and strategies should be developed for surveillance beyond ports, such as at premises where imported goods are first opened postborder. Training and education programs for biosecurity personnel, workers at ports, and industry in general are important in raising awareness and encouraging reporting of suspect ants.

Speedy eradication of an exotic invasive ant incursion is the desired outcome, but this may depend on a range of factors, including the extent of the ant's spread, how long it was present before detection, its biology, and the availability of tools for eradication. Standardized response procedures are required to support rapid response and a consistent approach throughout the eradication program (18). Procedures that should be documented include methodologies for surveillance, definitive diagnostics, treatment, tracing, quarantine controls, and community engagement.

### Management of Established Populations

Should an invasive ant population become established in a country and eradication not be possible, a range or combination of other options can be pursued. The first is aggressive containment, which has most of the elements of eradication. It should be, but is not always, much less expensive than eradication because it is not necessary to insure that all areas are treated, that all colonies are killed, or that all colonies are discovered and removed from buffer areas. It has the effect of buying time until new eradication tools are developed. Localized eradication or control of certain infestations may be conducted to suppress the ant and protect key assets (biodiversity, agriculture, human health) (e.g., 17). Quarantine measures can be put in place to slow the spread of the invasive ant, particularly measures targeting long-distance human-mediated dispersal (e.g., 8). Investigations may be undertaken into biological control and genetic tool options, although it should be noted that no effective biological control of ants has been achieved to date.

## FUTURE NEEDS

It is a biosecurity axiom that the earlier an invasive species is detected, the better are the chances of eradication, yet early detection is an area of vulnerability for many developing countries. This is well illustrated by the spread of the little fire ant and yellow crazy ant across islands in the Pacific in the past few decades; by the time their presence was recognized, it was already too late to mount a response because of resource limitations, both financial and human.

Future approaches to managing invasive species should include preparation of strategies to avoid or mitigate future invasions. The following efforts will contribute to preventing the introduction of exotic ants: (*a*) enhancement of current biosecurity surveillance by implementing adequate operational procedures, i.e., improvement in offshore surveillance, inspection, treatment of trade goods, and freight containers; (*b*) creation of a central repository or linked network of Asia-Pacific countries for knowledge relevant to the management of exotic ants; (*c*) increased science-based knowledge, innovation, and expertise for management of exotic ants in Asia-Pacific countries; and (*d*) development of generic, specific, and context-dependent contingency plans to mitigate migration of ants and their management.

## DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

## ACKNOWLEDGMENTS

We want to thank Dr. John Fellowes for his editing of the preliminary version of this review. Many of the topics and ideas that we cover in this review have also been informed by discussions with him over the past decade. We also thank Drs. Babar Hassan and Junaid Ali Siddiqiui for reading and editing drafts of the manuscript. This work was supported by funds awarded to Y.X. by the National Natural Science Foundation of China (grant 31772228), and E.L.V. was supported by the Urban Entomology Endowment of Texas A&M University.

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Volume 67, 2022

# Contents

## Errata

An online log of corrections to *Annual Review of Entomology* articles may be found at http://www.annualreviews.org/errata/ento