

Article

Eradication and Control Strategies for Red Imported Fire Ants (*Solenopsis invicta*) in Taiwan

Helen K. Liu ^{1,*}, Chung-Chi Lin ^{2,3}, Li-Hsin Huang ⁴, Sin-An Huang ³ and Rong-Nan Huang ^{3,5,*}

¹ Department of Political Science, National Taiwan University, Taipei 10617, Taiwan

² Department of Biology, National Changhua University of Education, Changhua County 50007, Taiwan; cclin@cc.ncue.edu.tw

³ National Red Imported Fire Ant Control Center, Council of Agriculture, Executive Yuan, R.O.C. (Taiwan), Taipei 10617, Taiwan; rivenser@gmail.com

⁴ Department of Pesticide Application, Taiwan Agricultural Chemicals and Toxic Substances Research Institute, Council of Agriculture, Executive Yuan, Taichung 41358, Taiwan; lhhuang@tactri.gov.tw

⁵ Department of Entomology, National Taiwan University, Taipei 10617, Taiwan

* Correspondence: helenliu4@ntu.edu.tw (H.K.L.); rongent@ntu.edu.tw (R.-N.H.)

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Abstract: Invasive alien species are one of the major threats to biological diversity, public safety, agriculture, and economics. In recent years, a new wave of the red imported fire ant (RIFA) has been detected in new regions, including Kobe (Japan), Daegu (South Korea), Kaohsiung (Taiwan), and other locations in southeast Asia. Due to the increasing number of invasions, practitioners and scientists are seeking effective strategies to respond to RIFA invasions in Pacific regions, especially in countries that have had no presence of RIFA. This study aims to identify the strategies adopted to eradicate RIFA in Taiwan and to elucidate some of the assumptions about RIFA prevention and treatment in infested areas with diverse land patterns. Through a literature review and examination of eradication cases in Taiwan, five essential eradication lessons are discussed: (1) Immediate action through partnership with universities and the private sector; (2) engagement with the public and community with an interest in RIFA control through technology; (3) establishment of multi-level horizontal networks of response teams; (4) strategy implementation ranging from large-scale prevention to precise treatment; and (5) adoption of technology and social media. These strategies will have implications and applications for east and south Asian countries that are dealing with similar challenges.

Keywords: invasive alien species; red imported fire ants; eradication; Asia; Taiwan; *Solenopsis invicta*

1. Introduction

Invasive alien species (IAS) are one of the major threats to biological diversity [1], public safety, agriculture, and economics [2]. The red imported fire ant, *Solenopsis invicta*, is a native of tropical and subtropical South America, and is known as one of the top 100 worst invaders globally [3]. In recent years, a new wave of the red imported fire ant (RIFA) has been detected in new regions; for example, in Kobe, Japan in 2017 [4] and in Daegu, South Korea in 2018 [5]. Meanwhile, in 2018, an increasing number of cases were reported in northern Taiwan and at a new site in Kaohsiung, located in south Taiwan.

The first invasion wave of RIFA occurred in the United States in the 1930s and eventually underwent global expansion [6], moving to Australia in 2001, Taiwan in 2004 [7], and China in 2004 [8,9] through increasing international trade [10,11] and a possible bridgehead effect [12]. A second invasion wave was reported to have originated in China in recent years. Most recently, further spread of RIFA is inevitable because their presence is deeply entrenched in some of the world's largest trading countries,

and, thus, lessons learned from the past are important for future prevention and sustainability [11]. Due to the increasing number of invasions in recent years, practitioners and scientists are seeking effective strategies to respond to a new wave of RIFA invasions in Pacific regions, especially in countries that have had no presence of RIFA previously.

Existing research details a rich experience and strategies for effective RIFA eradication. In particular, the availability of new treatment methods for RIFA control and treatment [13,14], advancement of technology, such as aerial surveillance [15], Geographic Information System (GIS) measurement and modeling predictions [16,17], and biological identification [18], will improve the success rates of RIFA eradication. Successful eradication cases have also been systematically reviewed in terms of the treatments [19], strategies [18], and policies [11] used.

Most documented RIFA eradications have taken place in more homogenous landscapes and lower population density areas. For instance, most eradication experiences and lessons learned have come from the US and Australia [18,19]. However, more recent invasions have taken place in areas with a high human population density and heterogeneous land uses. For instance, in Taiwan, instead of application using helicopters or aircraft, prevention teams can mostly use hand-held devices or all-terrain vehicle (ATV) quad bikes for bait spraying because of the complex landscapes involved. Therefore, additional examination of the eradication strategies is required.

The purpose of this study is to explore effective RIFA prevention management strategies through an analysis of effective eradication cases in urban and high population density areas in Taiwan. We ask the following question: What effective eradication strategies are described in the existing literature or were used previously in Taiwan in areas with diverse land uses and a high population density? Specifically, this study aims to identify the strategies adopted to effectively eradicate RIFA in Taiwan and to elucidate some of the assumptions about RIFA prevention and treatment in infested areas with diverse land use patterns. We conducted a systematic literature review on the eradication of RIFA and then selected unique cases from Taiwan. We chose Taiwan for our case study because there have been few in-depth publications on eradication in Taiwanese cities or counties since the first discovery of RIFA in Taiwan in 2003 [7,20]. In addition, this area is unique because it includes a variety of land use patterns when compared to the US or Australia, which have RIFA-infested areas. For instance, in Taiwan, the average farm area is 0.72 ha/family, which is far less than in the US and Australia. Diverse land use types increase the difficulty of surveillance and bait spraying for RIFA. Through this study, we provide strategies for RIFA eradication that will have implications and applications for eastern and southern Asian countries that are dealing with similar challenges.

2. Materials and Methods

Given the rich experience detailed in the literature on RIFA prevention and controls, using the Web of Sciences database, we first conducted a systematic literature review of publications describing prevention strategies for RIFA and other invasive ants that have been developed in the past 20 years. We adopted the keywords RIFA, *S. invicta*, invasive ant, and eradication. The initial search returned 907 articles. Then, we applied three inclusion criteria to gather relevant studies: (1) The study involves any type of invasive ant, (2) the study describes prevention strategies and/or actions, and (3) the study has a focus on eradication. After the initial screening, we reviewed 35 articles. The search was complemented by the snowball sampling strategy by selecting papers that cited key RIFA eradication papers, e.g., [19,21–23] and articles published after 2016. We focused on 63 articles.

In particular, Drees' study showed that integrated pest management (IPM), which combines cultural, biological, regulatory, and chemical tactics, is essential to keep population levels below those that cause economic, social, or ecological damage. IPM should include management goal(s), action level(s), consideration of the ant social form (monogyne or polygyne), whether non-target ant species are present, the size of the treatment area, seasonality, implementation costs, and environmental impacts [21]. Given the importance of IPM, our case study adopted the framework used by Drees et al. [21] to illustrate the eradication process. This involved four key processes that were carried out at three

relatively isolated infestation sites in Taiwan: (1) Discovery, (2) impacts, (3) treatments and controls, and (4) eradication.

Case Selections

In October 2003, the Bureau of Animal and Plant Health Inspection and Quarantine, Council of Agriculture under the Executive Yuan in Taiwan confirmed the first invasion case of RIFA via a farmer who was stung in a village located in Taoyuan City (Northern Taiwan). Through early inspection and a survey in March 2004, the investigation team found RIFA in Chiayi county in the southern part of Taiwan in addition to Taoyuan City. Initial surveillance showed that at least eight cities and townships in three counties covering an area of 4000 hectares were infested with RIFA. After the establishment of the National RIFA Control Center (NRIFACC) in 2004, policies aimed to eradicate any occurrences of RIFA outside the quarantined zone established around Taoyuan City, as shown in Figure 1.

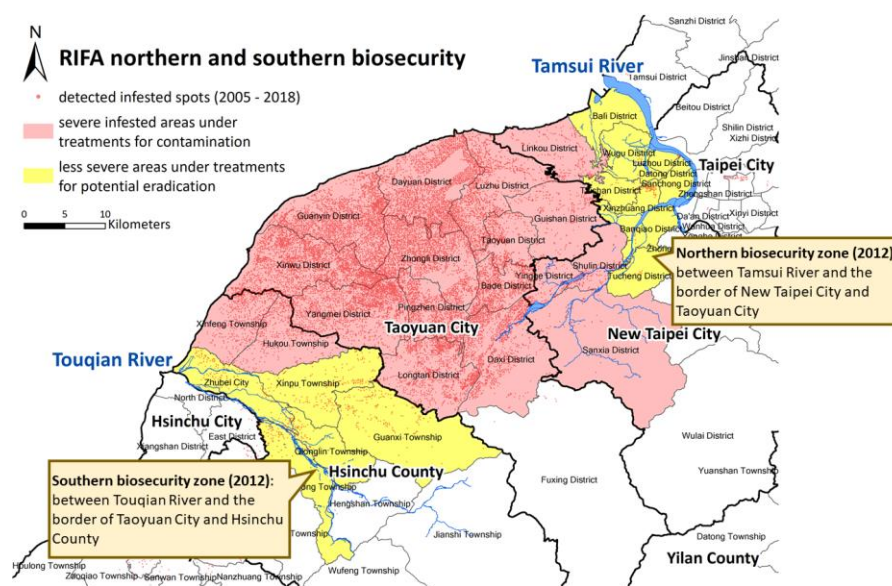


Figure 1. Geographical containment boundary of red imported fire ant (RIFA) in north-western Taiwan established in 2012. The red zone indicates severe RIFA-infested areas under treatment for containments. The yellow zone indicates less severe RIFA under treatment for potential eradications. According to a policy passed in 2015, RIFA occurrences outside the containment boundary should be targeted for eradication.

Though northern Taiwan was still seriously infested by RIFA, it did not spread widely from this area to southern or eastern Taiwan, which are the main agricultural sectors that are more suitable for RIFA habitation. Moreover, the sporadic RIFA presence in those areas was successfully eradicated. Given the varying situations faced by the prevention team, we selected three cases outside the quarantine zone and in different parts of Taiwan, namely Chiayi, Yilan, and Taichung, with different levels of infestation. By adopting a case selection method [24], we selected three cases with different invasion histories and characteristics in order to identify important factors that explain their different eradication outcomes. For instance, while Yilan and Taichung are sporadic cases, Chiayi serves as a large infested regional case. Figure 2 shows the locations of the three eradication cases that were investigated in relation to the biosecurity zones.



Figure 2. Geographical locations of the three eradication cases in Taiwan.

Furthermore, the compilation of eradication cases and processes presents some challenges given that some eradication processes lasted more than 10 years (such as the Chiayi case), and there were fewer publications in the earlier prevention stages in Taiwan. To overcome these challenges, we adopted the triangulation method detailed by Yin [24], which involved the collection of different types of data for each case study. Our data collection included data from research databases, government documents and reports, and interviews with individuals who had been involved in the eradication process.

3. Results

3.1. Trends from Literature on Establishing RIFA Eradication Plans

Our review of the most recent literature reveals new trends for RIFA eradication planning (Table 1). Recent studies focused on the identification of invasive ants [25], the prediction of the spread and its prevention [26–31], social economic impacts [32], environmental impacts [33–36], treatment and control [9,13,14,37–42], and genetic and biological identification methods [7,18,20,43], as well as technology adoption, such as digital data collection [22], aerial surveillance [15], and GIS measurements [16,17].

Table 1. New trends for RIFA eradication planning.

New Methods	New Threats
New treatment options [9,13,14,37–42]	Second wave of spread [4,5,11]
Advancement of technology [7,15–18,20,22,43]	New cases in urban and other areas that will have economic impacts [32]
New eradication efforts [19]	Settlements of RIFA in high-risk areas, such as schools and residential areas [44]

Moreover, there are immediate threats that required us to re-examine the control and treatment strategies given the occurrence of a second wave of invasion [4], including increased trading [10] and the discovery of new cases in urban and other areas that would have economic impacts [32], as well as cases in high-risk areas, such as schools and residential locations [44]. In addition, early prediction studies showed the aggressive spread of RIFA. For instance, Scanlan and Vanderwoude [28] adopted a stochastic cellular automation model to show that RIFA could cover up to 4 million km² in Australia by 2036 when accounting for spread within an area of 100 × 100 km and human-mediated movement of RIFA to new locations. Therefore, by analyzing eradication cases in Taiwan, this study aims to provide effective strategies for potential eradication planning.

3.2. The Development of RIFA Invasion Response and Prevention in Taiwan

The NRIFACC is a sub-unit under the Council of Agriculture. When RIFA was first discovered in 2003 in Taiwan, there was no established unit to handle this new invasive alien species. Learning from overseas experiences, in 2004, RIFA was declared a pest and, in response to the invasion, the NRIFACC was established by partnering with academic institutions. A number of guidelines were adopted and implemented to prevent the spread of RIFA, including (Table 2): (1) The announcement of RIFA as quarantined pests; (2) bans on the movement of flowers, seedlings, and soil transfer without RIFA-free certification; (3) announcement of the quarantine and inspection guidelines for imported plants or products; (4) consolidation of the National Three-Year Action Plan (2005–2007) for the reduction and eradication of RIFA; and (5) increased public awareness and reporting of RIFA [45]. In particular, the main contents of the National Three-Year Action Plan included the collection and research of RIFA, establishment of a reporting system, purchase of treatments and equipment, plans for monitoring and prevention, staff training, and medical treatment guidelines.

Table 2. Key strategies for RIFA management adopted by the Council of Agriculture, Executive Yuan in Taiwan.

Governments	Management Goal	Key Strategies
Council of Agriculture; local governments	Lower RIFA density or achievement of eradication	<ol style="list-style-type: none"> 1. Declare RIFA as a pest in need of quarantine. Escalate movement controls for plantation, nursery stock, potted plants, mulch, etc. (Sept. 2004). 2. Establish a National RIFA Control Center jointly with an academic institution (Nov. 2004). 3. Announce “Quarantine Requirements for Importation of Plants or Plant products into the Republic of China” for quarantine regulations (Dec. 2004). 4. Initiate the “RIFA Three Year Eradication Plan” (2005–2007) to gradually reduce infested regions and density. 5. General RIFA awareness training for community surveillance and prevention efforts (2004–present).

Source: Bureau of Animal and Plant Health Inspection and Quarantine, National RIFA Control Center (NRIFACC), under the Council of Agriculture, Executive Yuan in Taiwan.

The early control strategies included large-scale joint prevention and control, strengthening the prevention of routes through human activities, and defining the boundaries of prevention and control areas (infested areas and buffer zones), as well as long-term monitoring of high-risk areas [45]. By 2009, following four years of implementation of the eradication plan, there were some successful spot eradication cases, such as in the Shihmen Reservoir in the northern part of Taiwan [44].

However, governments and experts had also learned of further RIFA spread into new areas, despite the success of some of the monitored areas. Given the larger infested area (10 out of 11 townships in Taoyuan city), the strategies for RIFA prevention and control were modified to “containment and progressive eradication.” In addition, an early investigation team showed that monogynous and polygynous RIFA have different distributions across different counties, with Taoyuan accounting for 83.16% of the polygynous RIFA in Taiwan between 2003 to 2005 [46]. Given the different percentage distributions of monogynous and polygynous RIFA, Yang et al. [7,20] suggested that separate management units should be adopted to treat different infested areas with two isolated RIFA populations. Therefore, the RIFA-infested areas were divided into four zones from the north to the south of Taoyuan (Figure 1), in which different intensities of baits were applied.

By 2012, due to the decrease in the financial budget for RIFA prevention and treatment, new strategies and policies were implemented. These focused on the “hot spot and high-risk

zones” rather than large-scale treatment and prevention. The boundary for containment was set between the northern border (New Taipei County and Taoyuan County) and the southern border (Taoyuan County and Hsinchu County) (see Figure 1). Three types of prevention and treatment were defined: (1) Eradication of cases outside the boundary, (2) containment of cases on the defined boundary, and (3) suppression and monitoring for cases within the boundary. Figure 3 shows the timeline of major RIFA policies and invasion/eradication processes in the three selected cases in Taiwan.

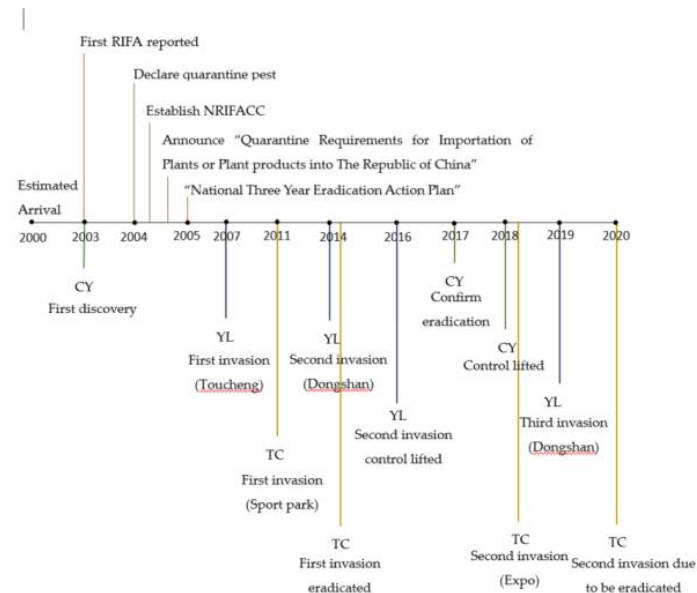


Figure 3. Timeline of major RIFA policies (above the timeline) and invasion/eradication processes in the three selected cases in Taiwan (below the timeline, where CY stands for Chiayi, YL stands for Yilan, and TC stands for Taichung).

3.3. Eradication Process: Monitoring, Treatment, and Control of RIFA in Taiwan

3.3.1. Monitoring of RIFA Infestation

To understand the occurrence of RIFA in Taiwan, the prevention team modified Bao’s [47] bait method by using potato chips to attract the foraging ants. The monitoring method used a 50 mL centrifuge tube containing a piece of original flavored potato chip that was put on the ground horizontally for 20–30 min. Then, the team returned the centrifuge tubes to the laboratory for RIFA identification under a microscope. Surveillance was usually performed during the day from 09:00–16:00 in sunny conditions and at a temperature of 20–35 °C. However, records show that some local governments may have modified the guideline with some variations.

3.3.2. Chemical Control of RIFA

A chemical strategy was the main method of RIFA control in Taiwan. Applications of bait, insect growth regulators (pyriproxygen, methoprene, or diflubenzuron), or toxic ingredients (cypermethrin, imidacloprid, or indoxacarb) were applied in RIFA-infested areas two–four times per year. The number of treatments varied across different cities and counties depending on their financial budgets. For those areas that were not easy to reach or apply bait, the long-lasting insecticide Fipronil was used instead. Mound injection with cyhalothrin was only applied when RIFA occurred in highly sensitive areas, such as elementary schools, densely populated parks, or outside the quarantine area.

3.3.3. Constraint and Restriction of Movement Control

Once RIFA was detected, the movement of soil and plants in the infested area was immediately constrained. The governments or private agencies of RIFA-infested areas were responsible for the

control and surveillance of RIFA according to standard protocols. Often, the NRIFACC offered technical support (e.g., treatments and surveillance training), while local governments (or private agencies) hired personnel to implement the treatments. Release from movement constraints required six consecutive months of surveillance and documentation of the absence of RIFA after the final treatment in the infested area.

4. Experience of Successful Eradication in Taiwan

4.1. Case of Chiayi County

Discovery

RIFA was first discovered in Chiayi County in October 2003. Following a series of sting attacks, the public was aware of the danger of RIFA, and a quarantine was declared 11 months after the first discovery [48]. In October 2004, the RIFA incursion squad was founded by a local farmer [48]. At the end of 2004, survey and control efforts were developed by the Bureau of Animal and Plant Health Inspection and Quarantine (BAPHIQ), Council of Agriculture, to define the boundary of the infested areas [48]. The Chiayi infestation spanned 15 villages: Shuishang township (Sanjie Village (Vil.), Guoxing Vil., Nanxiang Vil.), Zhongpu township (Jinlan Vil., Longmen Vil., Tongren Vil., Longxing Vil., Fushou Vil., Yiren Vil., Yumin Vil., Yanguan Vil., Hemei Vil., Dingpu Vil., Hemu Vil.), and Fanlu township (Neiwan Vil.), covering over 650 ha [48]. In addition, more genetic tests showed that the population of RIFA in Chiayi was different from that of Taoyuan city; it was originally transported from California through cargo shipments [10]. The infestation could have occurred as early as 2000, prior to its first discovery in 2003 [23].

Impacts

Southern Taiwan is the main agricultural area in Taiwan, and Chiayi is well known for rice production. It contains sunny, open areas, such as lawns, parks, pastures, meadows, and fields in which RIFA usually prefer to nest. Agriculture has played a key role in the provision of major foods, such as rice, in Taiwan. Invasive alien species and weather conditions are two key factors that might affect agricultural production. Farmers carry out agricultural operations and spend time on the farmland quite frequently. If invasions of the southern part of Taiwan are not effectively controlled, their impact on the environment, ecology, agricultural production, and public health would be far greater than the damage caused in the north.

Controls and Treatments

As an initial response in Chiayi, the team set up an alert zone spanning a 20 km radius from the first discovery site, which covered eighteen counties and cities [48], and adopted the “Two-Step Method” treatment program in November 2004 in the severe RIFA area. The two steps involved applying bait (spinosad, fipronil, and pyriproxyfen), and individual mound treatments using 85% carbaryl wettable powder [48]. The first round of control efficacy evaluation was only conducted after the second stage of treatment, due to a lack of pre-treatment of the mound density data. This was done as an urgent attempt to control the incursion, although the delimitation survey had not been completed [48].

The total area treated in Chiayi including the buffer zone was approximately 1100 ha. From November 2004 to December 2006, bait was applied four times per year by applying spinosad, fipronil, or pyriproxyfen, while pyriproxyfen served as the main type of bait [48]. After partial suppression of RIFA in 2007 with an above 90% control rate, the control intensity was divided by the level of RIFA density: A special treatment area and a regular treatment area [48]. Pyriproxyfen and indoxacarb bait was applied alternately four times per year in the special treatment area where the

RIFA density was high; otherwise, pyriproxyfen was applied twice per year in the regular treatment area [48].

Eradication

Table 3 summarizes the RIFA eradication process in Chiayi county. In 2017, the NRIFACC performed surveillance and detected no RIFA nests. The Council of Agriculture then declared and confirmed complete eradication of RIFA from Chiayi county in July 2017 [49]. The total area treated using the control and treatment methods mentioned above comprised nearly 1100 hectares. This area also included the 100 to 500 m buffer zone around the edges of the infested areas. The eradication process continued from 2004 to 2017, and final aerial bait treatments were applied to 35 ha near the Bazhang River, where the last RIFA nest was found in an area that was not easy to reach. All areas of Chiayi were surveyed by the NRIFACC in 2017 and no RIFA were found. RIFA-free approval requires no detection of RIFA for six months. Following a panel expert meeting held by the Council of Agriculture in 2017, an announcement was made that Chiayi county was removed from the RIFA restricted area, and controls were lifted in 2018.

Table 3. RIFA management summary in Chiayi county.

	Content	References
Discovered Location	Chiayi county: Shuishang (179.2 ha), Zhongpu (880 ha), Fanlu (4.9 ha), townships (total about 1046 ha).	[48]
Eradication Period	2003–2017.	[49]
Treatments/Methods Adopted	Application of spinosad, fipronil, pyriproxyfen, and indoxacarb; individual mound treatments with 85% carbaryl wettable powder in 2004.	[48]
Eradication Outcomes	Eradicated in 2015, followed by two more years of monitoring. Official announcement of eradication in 2017.	[49]
Lessons learned	Intensive cooperation with local farmer associations for RIFA management.	

4.2. Case Study of Yilan County

Discovery

Yilan county, located in the northeastern part of Taiwan, is isolated from RIFA-infested western Taiwan by the Xueshan mountains; however, it was still invaded by RIFA three times in 2007, 2015, and 2019 due to the transfer of soil for plantation and new construction development. The 2014 incursion of RIFA was first confirmed in April during the early rice-growing season, a time when it is difficult for ants to quickly spread, since fields are overflowing with water. In April 2014, a suspected RIFA nest was reported by the public near Dongshan River in Yilan, and samples were sent to the Hualien District Agriculture Research and Extension Station for identification. Delimiting surveillance concentrated on areas containing suitable habitats for RIFA, and this resulted in the detection of 200 mounds, including 10 working maps, with 147 ha requiring treatment [50].

Impact

Yilan is the main agricultural production area of northern Taiwan because of the availability of clean freshwater for rice irrigation [51]. RIFA is a major threat to various economic activities, particularly the recreation and tourism industry in the Dongshan township of Yilan county. The Dongshan river drainage basin is a key tourist destination in Yilan, where the children's play festival is held every year. A RIFA invasion could dampen tourism growth rates, as tourists understandably will find substitute travel destinations to avoid riverside parks packed with stinging ants or extensive amounts of pesticides [52].

Control and Treatment

A treatment area was established with a buffer zone of up to 100 m from the known infested areas. In 2016, an eradication plan was developed by BAPHIQ, the Government of Yilan County, and the NRIFACC for Yilan. This involved mound drenches and baiting the infested areas once every month with pyriproxyfen bait and granular fipronil [50]. The key factor in effective RIFA management in Yilan was the immediate action of the Department of Agriculture of Yilan County, which played a key role in successful elimination of the RIFA within a short time period. Immediate actions included the formation of the RIFA eradication response team, which included the Department of Environmental Protection, the Department of Public Works, the Department of Business and Tourism, the Department of Health, the Department of Economic Affairs, the Animal and Plant Disease Control Center of Yilan County, and the NRIFACC, who teamed up as a frontline group. The team held a meeting every two weeks to review (or survey) the progress of treatment.

Eradication

In December 2015, the eradication of RIFA in Yilan was progressing according to schedule, and all restricted areas were receiving regular surveillance once a month. The last RIFA nest, a single infestation, was found in Sanxing township in June 2016. Following emergency treatment, involving mound drench and pyriproxyfen bait on 14.29 ha for six months, the infestation in Yilan was destroyed in December 2016. Continued surveillance by the Animal and Plant Disease Control Center of Yilan county provided verification that treated areas were free of RIFA. In December 2016, after consultation with the NRIFACC, Yilan was removed from the list of RIFA restricted areas and controls were lifted. From 2014 to 2015, the area of eradicated infestation was around 161 ha [50].

However, in May 2019, a new RIFA infestation involving about 24 mounds was discovered in the Yilan Science Park flower field outside the declared restricted area. It is thought that the infestation may have been spread via transport of infested landscaping plants from another city [53]. The county government subsequently sent a team of professionals to exterminate the pests before they could expand within the treatment area any further. In addition to mound drenching, the surrounding area was treated with fipronil. The area covered approximately 38.7 ha [54] and follow-up surveillance was conducted after the final treatment to ensure eradication.

The unique characteristics of the Yilan case are its landscape, timing, and people. The unique landscape played a key role in large-scale spread and invasion, as the Xueshan Ridge acted as a natural buffer to prevent continued incursion. However, sporadic cases are still inevitable; therefore, RIFA monitoring efforts continue [55]. Table 4 summarizes the RIFA eradication process in Yilan county.

Table 4. RIFA management summary in Yilan County (with three independent invasions).

	Content	References
Discovered Location	Yilan county—Toucheng township (2007) 3.44 ha Yilan county—Dongshan township (2014) 127.96 ha Yilan county—Dongshan township (2019) 22.49 ha	[50]
Eradication Period	2007 (Feb.)–2007 (Nov.) 2014–2016 2019–present	[50]
Treatments/Methods Adopted	mound drenches, pyriproxyfen bait, fipronil granular	[50]
Eradication Outcomes	Eradicated 2007, 2016 Re-invaded 2019–2020 (expected)	[56]
Lesson Learned	Early detection and immediate action with the responsible agency	

4.3. Case of Taichung County

Discovery

Taichung county is located in the mid-west part of Taiwan, which is approximately 90 km from the major RIFA infestation area and was invaded by RIFA twice, in 2011 and 2018. The first known RIFA invasion took place in 2011; an elementary teacher reported a suspected RIFA infestation to the NRIFACC. It was detected in an athletic park near Kanglang Elementary School in Qingshui District. Soon, surveillance was conducted by the NRIFACC, which resulted in the detection of another two mounds in the redevelopment district near Kanglang athletic park. RIFA was likely introduced to the area via nursery stock or construction equipment.

Another invasion took place at the World Flora Exposition (20 km from the area of the first invasion in 2011). On 2 November 2018, the second day of the Taichung World Flora Exposition, a volunteer reported the first sighting of a single mound in the turf grass at the entrance to the NRIFACC. It has been shown that human-assisted dispersal is much more damaging than natural nuptial flight spread, as it can easily transport insects over a long distance through soil or nursery stock, as has been shown in Australia [57].

Impact

Taichung county is located in the mid-west part of Taiwan. Differently from Chiayi and Yilan, Taichung is known for its shipment port and industrial activities. Taichung is also the third largest city in Taiwan by population, with nearly 3 million residents. Given that Taichung was not within the quarantine boundary, public reporting and awareness were crucial. The success of eradication in Taichung relied on public reports. Therefore, the public reporting system was essential for the eradication process. Both RIFA invasions were reported by the public in 2010 and 2018. Given Taichung's importance in industrial and residential developments, RIFA threaten the safety of ports and public health, and potential spread could occur through high-level human transmission activities.

Control and Treatment

There have been three cases in the Qingshui District. On 12 December 2011, the NRIFACC received samples from a sports park (Figure 4a), which were then confirmed as RIFA. Ten nests received individual mound treatment with contact insecticides (indoxacarb and granular fipronil). Furthermore, on 12 December, the NRIFACC researchers discovered another mound near the reported site (Figure 4a) in the redevelopment area. The granular formulation, indoxacarb, and 0.0143% fipronil were applied uniformly to the soil surface. Post-treatment surveillance was extended to 100 m beyond the nest on all sides on 21 December. On 28 December, a suspected RIFA infestation was found at the Siwei Road and Dayong Road intersection (769 m from the initial site). Following surveillance by the NRIFACC, 22 nests were confirmed to be a RIFA infestation. The treatments adopted were mound drenching (cyhalothrin 2.46% CS) and baiting with pyriproxyfen (0.5%). All three cases of sporadic RIFA were situated in the surroundings of a sports park in the Qingshui District and the nearby redevelopment district (Figure 4a). Figure 4b shows the size of RIFA mound found in the discovered site.

For the second invasion, which took place at the Flora Exposition, the treatment team was led by researchers from the National Changhua University of Education. The team conducted surveillance at four sites of the Taichung World Flora Exposition: The Houli Horse Ranch, Forest Expo Site, the Waipu Expo Site, and the Fengyuan Huludun Expo Site. The Houli Horse Ranch and Forest Expo Site covered 30.04 ha, the Waipu Expo Site covered 14.32 ha, and the Huludun Expo Site covered a total of 16.25 ha. The director of the NRIFACC and the director of Kunlong BAPHIQ enlisted the Agriculture Bureau to educate expo stakeholders and ensure that consistent and accurate information reached them.

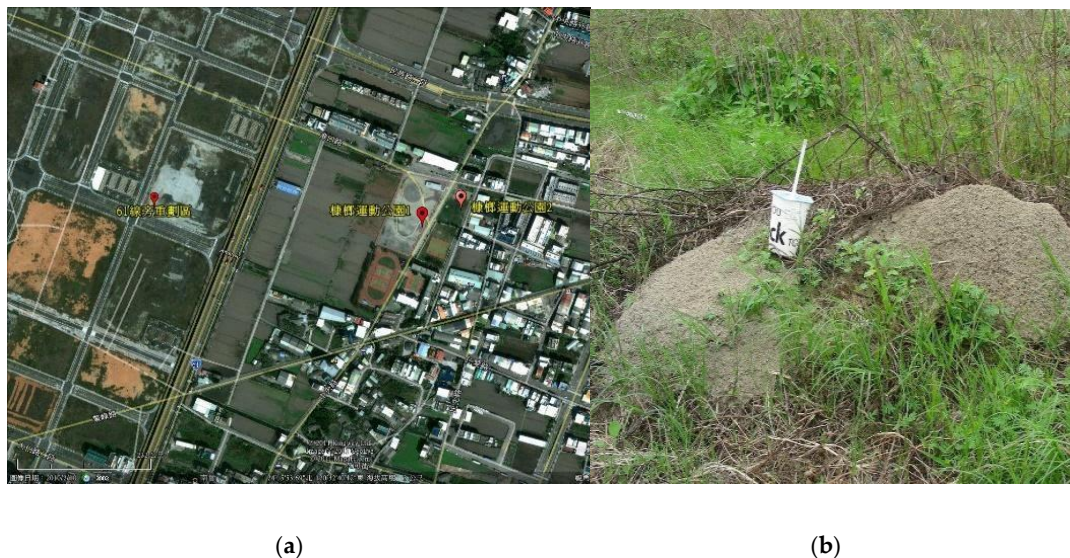


Figure 4. (a) Location of the RIFA found in Taichung Qingshui. From left to right: RIFA colony found in the redevelopment area, sports park, and the intersection (in red marks); (b) the size of the RIFA mound.

Figure 5 shows the location of the RIFA mound discovered at the flora expo site. Surveillance was also conducted to ensure that RIFA had not spread beyond the current boundary and to detect any new nests. Treated sites were surveyed every three months, with the field divided into plots. Evaluation involved detecting the RIFA nest and collecting the ants that were present, which were later identified. The numbers of ants of different species were pooled for analysis.

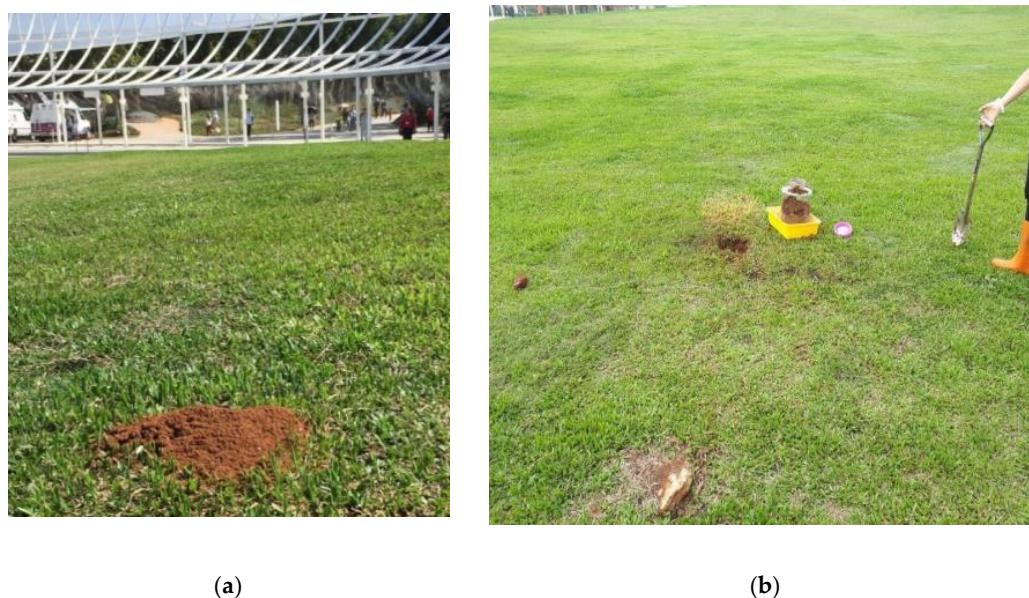


Figure 5. Location of the RIFA mound discovered at the flora expo site. (a) Mound on the turf surface at the Taichung World Flora Exposition entrance in Taichung (2 November 2018); (b) removing the mound and applying pyriproxyfen (6 November 2018).

In December 2018, one month after treatment, four RIFA nests were collected from 1661 plots at all sites, while no RIFA were found in Houli Forest (Table 5). In January 2019, the survey found six RIFA out of 1651 plots, and the number in Houli Forest remained at zero. The RIFA capture rate remained at 0.2% in March and May. After 14 months (January 2020), the control efficacy rate reached 100%, with no RIFA detected in any plot (Table 5). Each survey result is shown in the tables below.

Table 5. RIFA surveillance in four expo sites in Taichung from Dec 2018 to Jan 2020 (Plot refers to the number of baits placed; Count refers to number of RIFAs found; % refers to percentages of RIFA found; Count (Other ants) refers to number of other types of ants found in the same baits; % (Ants) refers to percentages of other ants found in the same baits.

Field Site	Plot	Count (RIFA)	% (RIFA)	Count (Other Ants)	% (Ants)
Dec-18					
Houli Forest	417	0	0.00%	107	25.70%
Houli Horse Ranch	380	1	0.30%	109	28.90%
Waipu	500	1	0.20%	184	37.00%
Huludun	364	2	0.50%	96	26.90%
total	1661	4	0.20%	496	30.10%
Jan-19					
Houli Forest	447	0	0.00%	40	8.90%
Houli Horse Ranch	357	3	0.80%	33	10.10%
Waipu	505	1	0.30%	62	18.40%
Huludun	342	2	0.40%	34	7.10%
total	1651	6	0.40%	169	10.60%
Mar-19					
Houli Forest	377	1	0.30%	39	10.60%
Houli Horse Ranch	366	0	0.00%	42	11.50%
Waipu	376	1	0.30%	59	16.00%
Huludun	424	1	0.20%	73	17.50%
total	1543	3	0.20%	213	14.00%
May-19					
Houli Forest	327	2	0.60%	71	22.30%
Houli Horse Ranch	297	1	0.30%	59	20.20%
Waipu	315	0	0.00%	51	16.20%
Huludun	371	1	0.00%	79	21.30%
total	1310	3	0.20%	260	20.10%
Jan-20					
Houli Forest	77	0	0.00%	54	70.10%
Houli Horse Ranch	171	0	0.00%	89	52%
Waipu	151	0	0.00%	100	66.20%
Huludun	0	0	0.00%	0	0.00%
total	399	0	0.00%	243	60.90%

The team formed by researchers from the National Changhua University of Education, working closely with NRIFACC, was in charge of the expo field surveillance, and contractors were responsible for implementing the treatments. However, the survey results suggest that there was some degree of misuse of insecticide. In October 2019, surveillance detected no RIFA infestations in the Houli Forest Expo site, yet a large volume of unspecified granular material was applied at the site. The Agriculture Bureau was informed that 0.3% fipronil bait was applied instead of the 0.0143% fipronil granular insecticide recommended for RIFA. In Taiwan, 0.3% fipronil is formulated for application on rice and corn. Fipronil residue has frequently been found in the pollen carried by poisoned bees, mainly areca pollen and camellia pollen. Misuses of treatments by private contractors present challenges in the RIFA management process and the environment.

Eradication

The three cases in Qingshui District, Taichung were removed from the restricted zone on 26 September 2014. Early detection and intensive control treatments contributed to effective and

successful RIFA eradication, and the early detection outside the quarantine zone, such as cases in Taichung, relied on public reporting.

Since the infestation of RIFA in the flora expo had a wider spread within a short time due to the plantation, a RIFA control meeting was immediately launched by the Taichung Government in February 2019. This involved multiple agencies, including the Construction Bureau, Tourism and Travel Bureau, Water Resources Bureau, Education Bureau, Urban Development Bureau, Land Administration Bureau, and Indigenous People Commission. The NRIFACC director conducted workshops on the management and biology of RIFA. The meeting also established “The Taichung World Flora Exposition RIFA Eradication Program” as a guideline for industry groups, contractors, and suppliers to follow.

Controls in the Huludun Expo Site were lifted in October 2019. Surveillance indicated that the other three expo sites (Houli Forest Site, Houli Forest Ranch Site, and Waipu Site) had been free of RIFA continuously for 3–6 months in December 2019 and January 2020. All areas are due to be removed from the restricted zone in June 2020. Furthermore, considering that the initial RIFA incursion at the Flora Expo site resulted from the movement of infested soil and container plants, the Taichung government included a “no RIFA” policy in the construction contract. A RIFA-free inspection is required at the end of construction. Government bodies, earthwork contractors, and landscaping suppliers will have to work together closely to prevent RIFA invasions in Taichung City center. Table 6 summarizes the RIFA eradication process in Taichung county.

Table 6. RIFA management summary in Taichung county (two independent invasions).

	Content	References
Discovered Location	<ol style="list-style-type: none"> 1. Qingshui District (33 mounds scattered in several areas that distanced 769 m away) 2. Four expo sites located in three districts (60.6 ha) 	[55]
Eradication Period	<ol style="list-style-type: none"> 1. 2011–2014 2. 2018–2020 	[55]
Treatments/Methods Adopted	Pyriproxyfen, 0.0143% fipronil	[55]
Eradication Outcomes	<ol style="list-style-type: none"> 1. 2014 eradicated 2. 2020 eradicated 	[55]
Lesson Learned	<ol style="list-style-type: none"> 1. Early detection from local residents and treatment contribute to effective eradication. 2. It is critical to regulate the movement of certain items that might carry ant infestations. Incorrect treatment resulted in biological damage, and it was suggested that further monitoring of bait application is necessary. 	

5. Discussion

The lead agency for the prevention and treatment of RIFA in Taiwan, the Bureau of Animal and Plant Health Inspection and Quarantine, has adopted general practices and scientific methodologies [18,19] to contain and eradicate RIFA in key areas. For instance, to strengthen the control and quarantine of RIFA, the agency has set clear zones and scope for the prevention and control areas, established nationwide unified control operations and prevention processes, trained professionals in pesticide use and recording, set guidelines for evaluation, established a public notification system, and set strict guidelines for the inspection and registration of pesticides for quarantine [44]. With these policies and treatments in place, RIFA are contained within prevention zones.

In this study, we selected three unique and representative eradication cases to illustrate the processes of eradication under various conditions and in different geographical locations. Our findings are in accordance with those of the empirical studies discussed above. With regard to RIFA prevention

and eradication, our findings confirm methods adopted internationally [18,19]. These results are linked to the following lessons.

Lesson 1: Immediate Action through Partnership with Universities and the Private Sector

The studied cases show that successful eradication begins by tapping into local resources through partnerships with local universities and private chemical companies. This enables the government to access specific knowledge on treating RIFA in different environments through working with the local universities, which allows local scientists to experiment with different combinations of treatments in order to eradicate RIFA in specific geographic locations. As mentioned earlier, through examining different RIFA populations in Taiwan, Yang et al. [7,20] suggested that separate management units should be established to manage different infested areas. Meanwhile, it creates more financial flexibility for the government to work with the local private sector to implement treatments in a timely manner.

The key factor in effective RIFA management is immediate action. For instance, in Yilan, the Department of Agriculture of Yilan County played a key role in successful elimination of RIFA in a very short duration. The immediate actions included the formation of the RIFA eradication response team within two weeks, as well as the NRIFACC. Through public and private partnership with a local chemical company, the local county was able to access essential treatments for preventative work rather than waiting for budget approval.

Lesson 2: Engagement with the Public and Community with an Interest in RIFA Control through Technology

A previous study showed the effectiveness of engaging the public through digital data collection [22]. Those eradication experiences show the importance of public education in uninfested areas so that the local public can report infestations immediately, allowing early prevention and treatment to be achieved. In all three cases, given that the infestation areas were outside the prevention and control zone, the discovery of the first cases relied on public reporting to prevent more spread of RIFA in those popular tourist areas.

In Taiwan, several educational channels have been established along with a public reporting platform, named Epidemic Net, which allows the public and local agencies to report cases, particularly those outside the monitoring zones. In general, in Taiwan, the public is supportive of the treatment and control of IAS. For instance, Liu [58] showed that visitors support prevention and control in areas that affect their activities, such as national parks, and are willing to reduce recreational areas in order to minimize ecological disturbance and harm during the treatment and control process.

Similarly to Taiwan, Australia has accumulated a 16 year dataset of ant specimen submissions from data from public reports since the launch of a national red imported fire ant eradication program, engaging citizens in the fight against fire ants. In Australia, such community engagement is described as passive surveillance. This can increase the probability of eradication and reduce the total cost of managing an invasion. McNaught, Wylie, and Bell [59] recently showed that 95.7% of adult respondents (n = 601) had heard of red fire ants, 37.9% had checked their properties during 2013, and the level of awareness among respondents (n = 1005) was 89% by 2018. They concluded that the program was effective in educating people on how to recognize fire ants and that photograph submission is a cost-effective and successful engagement tool.

Lesson 3: Establishment of Multi-Level Horizontal Networks of Response Teams

Uniquely, in Taiwan, while the NRIFACC has been established, the government has also established a central and local inter-organizational prevention network to address the needs for different types of environmental conditions. The structure of the network involves the Council of Agriculture as the head agency, the NRIFACC as the coordination point, and the central and local governing authorities, which are responsible for different environmental conditions as well as political boundaries. For instance, while implementing the prevention and eradication of RIFA in the National or Metropolitan Parks, the Ministry of the Interior is the central governing authority, but if an infestation occurs in city parks

and other green spaces, the execution will be undertaken by the local city governments with the Ministry of the Interior as the supervisor.

The reason for such a design is due to the various environmental conditions that all occur within a small area and require different strategies and methods. Furthermore, the establishment of an inter-organizational response team could be adopted to deal with the unknown diffusion patterns of RIFA. In addition, it is also clearly cost-effective, as the government does not need to employ full-time staff at all times. One of the biggest management programs for RIFA control is the lack of full-time staff. With a high turnover rate of part-time staff, it is difficult to retain the experiences and knowledge for proper RIFA controls and eradication, which can take a number of years to accumulate. However, given that this inter-organizational process involves 22 central authorities and 22 local authorities, as well as private actors, it has required a tremendous coordination effort through technology and policy design [60]. This bottom-up design of the RIFA prevention network allows local authorities to experiment with different prevention methods that are suitable for the local climate, land use, and human interactions.

Lesson 4: Strategy Implementation Ranging from Large-Scale Prevention to Precise Treatment

Using the experience and research adopted from the US and Australia, the government established a large-scale prevention method in an earlier prevention plan [44]. The large-scale prevention approach focused on applying treatments in the infested areas and additional prevention areas within a radius of 2 km of the infested sites for monitoring, because previous research shows that RIFA can travel up to 1.6 miles to establish new colonies. However, with a high-density population and diverse landscapes, large-scale prevention has been ineffective. For instance, the prevention teams often have difficulty accessing private landowners' homes, storage areas, and new development areas. In addition, different types of landscapes require different treatment methods. For instance, mound drenching with toxic insecticides is not allowed in water source protection areas and organic farms. Therefore, as mentioned earlier, the four-year eradication plan targeting large-scale prevention and treatment was not sufficient. However, at the same time, areas that have actually successfully eradicated RIFA from the entire county have often focused on precise treatment and prevention methods.

The precise treatment and prevention methods involve the following steps: (1) Confirmation of delimitation areas to spray insecticides, such as in Yilan and Taichung, so that the prevention teams can treat RIFA precisely; (2) adoption of GIS to track the RIFA invasion sites, as well as the control areas, for accurate prevention. To effectively eradicate a pest, it is important to develop a high-quality map [61]. The team focused on treatments within a radius of 100 m of the RIFA nests (the occurrence area), monitored a radius of 300 m, and set a control zone of 500 m. Setting up a manageable and precise boundary allows the team to experiment with different treatment combinations for different types of landscapes. Precise treatment is particularly important for high-risk areas, water reservoirs [23], schools [44], nursing homes [62], and urban areas, such as residents' homes [63].

Precise treatment should also include the consideration of the timing of the year, given that weather and temperature affect the development of ant colonies [64]. For instance, Killion and Grant's [63] colony-growth model shows that the number of workers in a colony is affected by the temperature. In successful eradication cases in Taiwan, treatments were often given before the expansion of the colony during the spring time.

Lesson 5: Adoption of Technology and Social Media

The eradication and prevention strategies established were mostly adopted from overseas, including from the US and Australia, during the early RIFA prevention effort in Taiwan. For instance, the NRIFACC set up a quarantine boundary with a radius of about 2.57 km, but soon realized that it was not suitable for Chiayi county. However, from the Chiayi example, they learned that if immediate actions were taken, a quarantine boundary could be set within the foraging area of the RIFA, with an estimated radius of 100 m for the treatment zone, 300 m for the prevention zone, and 500 m

for the monitoring zone. This was made possible through the adoption of GIS to identify and generate quality maps for precise measurement of the discovery and treatment points. The adoption of technology increased the accuracy of information sharing among team members and contracted pest control companies.

The prevention team from Yilan, for instance, developed another unique invention for the eradication process. Given its relatively remote location from the major infested areas, the members of the prevention team came from three different agencies located in two different cities. The prevention team established a Line group, a popular social media group for sharing information (such as sharing site photos and treatment information), thus providing immediate responses for technical support or to address difficulties encountered during the eradication process.

6. Conclusions

Although our demonstration of RIFA eradication in three unique cases presents lessons for RIFA prevention and control, it also shows the potential limitations of the existing practices. First, all three cases experienced re-invasion due to the transplant of nurseries and plants from outside the cities or counties. In other words, despite the prevention and control efforts from the local team, without a national prevention and control plan and regulation of the main human activities that can lead to RIFA transfer, the effort will be less effective due to re-invasion. Particularly challenging is that our cases were all at the city or county level, so a national effort, such as the regulation of transfer of soils and plants, was not documented. Moreover, some treatment methods applied in the early 2000s are no longer available due to the restrictions discussed by Hoffmann et al. [19]. Frequent human transportation of RIFA makes it more difficult to predict the movement of RIFA and initiate treatments.

Furthermore, the eradication process could take more than several years, as shown in the illustrated cases. The long process for RIFA eradications is due to three reasons: First, treatments such as fipronil do not kill RIFA, but control the growth of the RIFA colonies. The life cycle of RIFA queens is approximately seven years. For certain environmentally sensitive areas, fipronil might be the only treatment allowed and, thus, complete eradication is delayed. Second, using effective treatments for the first three years, 90% of RIFA can be eradicated. However, the last 10% are often the most challenging cases given their low visibility and high mobility. Therefore, conventional detection methods through observation or baiting often fail to identify the last 10% of RIFA, and special detection strategies, such as dog inspections, are needed. Multiple detection methods are required to certify the eradications. Lastly, re-invasions from outside the city through trade, nurseries, or plantations present another challenge to RIFA eradication. Nationwide policies on the monitoring of nurseries, soil, and plantations, as well as RIFA-free certification programs, should be in place.

Future studies should examine the implications of RIFA spread by human activities, such as via soil, plant, and nursery transfer. In addition, a combination of different treatments for different land types is also important for the control and prevention of RIFA expansion into mixtures of diverse habitats and landscapes. Another important area that should be considered in the design of RIFA eradication is the impact on other species [1,21,38,65,66]. For instance, Butler et al. [65] examined how the application of malathion ultra-low volumes (ULV) to treat boll weevil may impact RIFA survivorship, foraging activity, and predation of lepidopteran pests. On the other hand, RIFA are like other aggressive ants, such as *Myrmica rubra* [34] and the Argentine ant [67], which actively displace native ants and reduce biodiversity.

Currently, RIFA distribution is contained in northern Taiwan following its discovery in 2003, and the government continues to invest significant effort to prevent its spread southward. The eradication process of RIFA in Taiwan remains in the experimental stage. Much more also needs to be known about the effectiveness of various treatments in different land types. This study should provide insights for additional research. There is a continuing need for systematic review and documentation regarding the practical application of IAS management for various other invasive insects, such as the fall armyworm

and locusts, which also present great threats to the local agriculture and economy. In addition, this study will have implications for newly invaded areas, such as East Asia [4,5] and West Africa [68].

This study has demonstrated that a plan for eradication is needed, and this is emphasized by lessons learned from previous successful eradication cases in various land types in Taiwan. It follows that detection, quarantine, and treatment must be strengthened, and better methods of working with private companies, public engagement, and technology are needed for effective RIFA eradication. However, whether this will also apply to RIFA-infested areas in other parts of the world cannot be determined based on this study. Further research in different regions with different temperatures and land types is warranted.

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