Chapter 30

Fire ant IPM

David H. Oi and Bastiaan (Bart) M. Drees

Imported fire ants (*Solenopsis invicta, S. richteri* and their hybrid) are notorious invasive ants from South America that continue to plague the southern USA since their inadvertent introductions prior to the mid-1930s. They now infest over 129.5 million hectares in the USA. The red imported fire ant (*S. invicta*), commonly referred to as "fire ant," has continued to spread and is now a worldwide concern with infestations confirmed in Australia, Southeast Asia and Mexico. The painful, burning sensation that is inflicted by the sting of a fire ant is easily the most recognizable hazard to humans. While one sting is painful, it is not uncommon for a person to receive numerous stings simultaneously when ants swarm out of their nest to attack an intruder. This greatly intensifies the pain and can cause panic; thus fear or apprehension of these ants can be present in heavily infested or newly infested areas. In addition, it is conservatively estimated that 1% of stung individuals in the USA are allergic to the venom and at risk for anaphylaxis. Deaths from fire ant stings have been reported and lawsuits have resulted in awards of over $US 1 million.

Besides the costs associated with litigation, the annual economic impact of fire ants in the USA is estimated to be over $US 6500 million across both urban and agricultural sectors. In addition, their dominance in natural ecosystems has reduced biodiversity and harmed wildlife (Wojcik *et al.*, 2001). Given the tremendous impact that fire ants have had in the USA, incursions into previously non-infested areas have promulgated very expensive eradication programs. The cost of a planned, but aborted, ten-year eradication program in California was valued at $US 65.4 million (Jetter *et al.*, 2002). The current eradication program in Australia will cost over $US 144 million over 7 years (2001–2007, McNicol, 2006).

In the southern USA, eradication is no longer considered possible and instead, IPM for fire ants is evolving. The evolution of fire ant control strategies is an interesting mix of politics and science. The nasty sting and ubiquitous presence of fire ants makes its control politically expedient, and hence, the availability of funding makes fire ants the most intensely studied ant. In this chapter we discuss the historical transition of fire ant control strategies and illustrate how knowledge of the biology and ecology of fire ants advanced the development of IPM for this invasive pest.

30.1 Evolution of fire ant control: eradication/control attempts in the southern USA

The accidental introductions of fire ants into the USA through the port at Mobile, Alabama r-

Integrated Pest Management, ed. Edward B. Radcliffe, William D. Hutchison and Rafael E. Cancelado. Published by Cambridge University Press.

thought to have occurred in 1918 for the black imported fire ant (S. *richteri*) and 1933 for the red imported fire ant (Tschinkel, 2006). By 1937, the fire ants had spread west into the state of Mississippi and east across Mobile Bay in Alabama. The seriousness of the problem resulted in a combined county, state and federal government program to control the ants. An insecticide containing 48% calcium cyanide dust was injected into individual fire ant nests on over 800 ha of vegetable cropland, with 80% of colonies reported eliminated. During World War II (1941–45), control efforts and research on the fire ant problem apparently were suspended.

During the late 1940s more intensive research on fire ants by university and US Department of Agriculture (USDA) laboratories commenced and have continued to the present. In 1948, the Mississippi legislature appropriated $US 15 000 to begin a control and eradication program which entailed the application of chlordane dust to nests. Surveys undertaken in 1949 through 1953 documented the rapid spread of fire ants and indicated that transport of infested commodities, such as nursery plants, facilitated the dispersal to 102 counties in 10 southern states. However it was not until 1958 that a quarantine was instituted, prohibiting the movement of fire ant harborages such as sand, gravel, soil on timbers, grass sod and nursery plants, unless treated with insecticide to kill any ants.

Prior to the quarantine, emphasis was still on eradication using contact insecticides. In 1957, aerial applications of heptachlor were made in an eradication project in Arkansas and the USA. The US Congress appropriated $US 2.4 million for USDA to immediately conduct a cooperative federal–state control and eradication program. Within three months, quarantine (effective in May 1958) was proposed to limit the spread of fire ants and an eradication plan was conceived that called for aerial and ground applications of heptachlor or dieldrin. Early applications of heptachlor at 2.24 kg/ha occurred in the winter of 1957–58 and soon after wildlife and cattle deaths were reported. From 1959 to 1960 application rates of heptachlor were reduced drastically in response to environmental concerns. In early 1960, residues of heptachlor on harvested crops were no longer permitted because heptachlor degraded into a more toxic compound, heptachlor epoxide, thus preventing treatment of cropland. The exclusion of cropland made eradication impractical because all infested areas could no longer be treated. The failed eradication attempt with heptachlor and dieldrin and the severe consequences to the environment was one of the events described in Rachel Carson's 1962 book *Silent Spring* which brought to the forefront public awareness of the environmental consequences of pesticides.

Concurrent with the heptachlor eradication program, research was being conducted at university and USDA laboratories to improve control methods. Delivery of insecticide via a bait formulation was a way to reduce the amount of insecticide applied to the environment. Ant baits are comprised of a slow-acting insecticide mixed into a food fed upon by ants. The slow action of the insecticide allows time for the natural ant behaviors of foraging and transferring food among ants within a colony to distribute the insecticide before causing death. The active ingredient mirex incorporated into a food attractive to fire ants and compatible with conventional insecticide application equipment was developed in 1961 and by 1963 refined into a standardized ant bait formulation. The bait had an application rate that resulted in 8.4 g of active ingredient per ha (which two years later was reduced by half).

Because of the low amount of mirex needed for effective fire ant control and application of such a small amount of insecticide that had less acute toxicity than DDT, a very widely used insecticide, the mirex bait was not considered to be hazardous to humans and animals at that time (Lofgren *et al.*, 1963; Lofgren, 1986). The cooperative federal–state fire ant control program continued to use mirex bait from 1962 to 1978, with an estimated 18.6 million ha treated three times, which encompassed almost all the infested states (Williams *et al.*, 2001). Unlike heptachlor and dieldrin, mirex bait did not have residual toxicity to fire ants and thus serial applications were needed when treated areas became reinfested. Lofgren & Weidhaas (1972) calculated three to nine applications with 90% to 99.99% control would be needed to eradicate fire ants from an 809.7 thousand ha area.

Despite the early eradication attempt and ongoing control programs, fire ants continued to spread and political pressure was still sufficient for another eradication attempt to be proposed. Congress appropriated funds in 1967 to the USDA to conduct large-scale tests to determine the feasibility of eradicating fire ants with mirex bait. Studies were conducted from 1967 to 1970 on three sites that ranged in size from 103 600 to 862 750 ha. It was concluded "that technical problems we did encounter are surmountable and, therefore, total elimination of IFA [imported fire ants] from large isolated areas may be technically feasible" (Banks *et al.*, 1973). However, the proposed eradication program was never implemented because in 1970 the use of mirex was challenged by environmental groups and banned from use on land managed by the US Department of the Interior.

The newly created US Environmental Protection Agency (EPA) held public hearings from 1973 through 1975 to review the use of mirex. Studies in the late 1960s and into the 1970s indicated that mirex residues persisted in the environment and accumulated in the tissues of non-target organisms, and that residue levels were magnified in predators that ate contaminated prey and were toxic to estuarine organisms. Mirex was also found to be carcinogenic and its use was forbidden after 30 June 1978. During the legal challenges and public hearings, the application of mirex bait continued and even after mirex was banned there was an effort to register a biodegradable formulation of mirex bait called ferriamicide. However, this product was never commercialized as it also persisted in the environment.

With the environmental concerns and legal challenges against the use of mirex, the USDA accelerated an effort to find alternative fire ant bait toxicants. From 1976 to 1981 over 3000 chemicals were evaluated resulting in the registration in 1980 of the fire ant bait Amdro® (which contained the active ingredient hydramethylnon). This product is currently available. Several other fire ant baits were developed since the registration of Amdro®, including insect growth regulating baits and fast-acting baits that are effective within three days in contrast to the two to four weeks for traditional baits (Oi & Oi, 2006). The acute toxicity of active ingredients used in currently available fire ant baits is generally much lower than the insecticides used for fire ant control before hydramethylnon (Table 30.1). No further attempts at the eradication of fire ants from the southern USA have occurred since the cancellation of mirex.

In hindsight, fire ants, with their painful sting and easily recognized nests, made their spread alarming. Public outcry and political pressure to eliminate the venomous invader, and the confidence during that era of the recently discovered synthetic insecticides to eliminate pests led to the regrettable widespread applications of heptachlor and dieldrin. With the development of the mirex bait there was a very significant reduction in the amount of insecticide applied and an assumption that it was not hazardous to humans and wildlife. Certainly acute mammalian toxicity was not apparent, but its environmental persistence and biomagnification were not anticipated. In addition, its effect on non-target arthropods, especially other ants that would feed on the bait, may have facilitated fire ant reinfestations and their spread into habitats not dominated by fire ants (Markin *et al.*, 1974; Buren in Canter, 1981, p. F-29).

During the period of the large-scale eradication and control programs, the area under the fire ant quarantine still continued to expand. However, these programs most likely operated under the logistical and technical problems identified in the eradication feasibility trials. Thus, while the eradication of fire ants from the southern USA was a goal, technologies, such as environmentally compatible, species-specific control methods were not available to eliminate fire ants and return and/or retain the native ant ecosystem over millions of hectares. Nevertheless, the development of insecticidal fire ant baits for the eradication/control programs provided the basis of a control tactic (i.e. broadcast application of bait-formulated insecticide) that continues to be the most efficient and environmentally compatible method of reducing fire ant and other pest ant populations (Fig. 30.1).

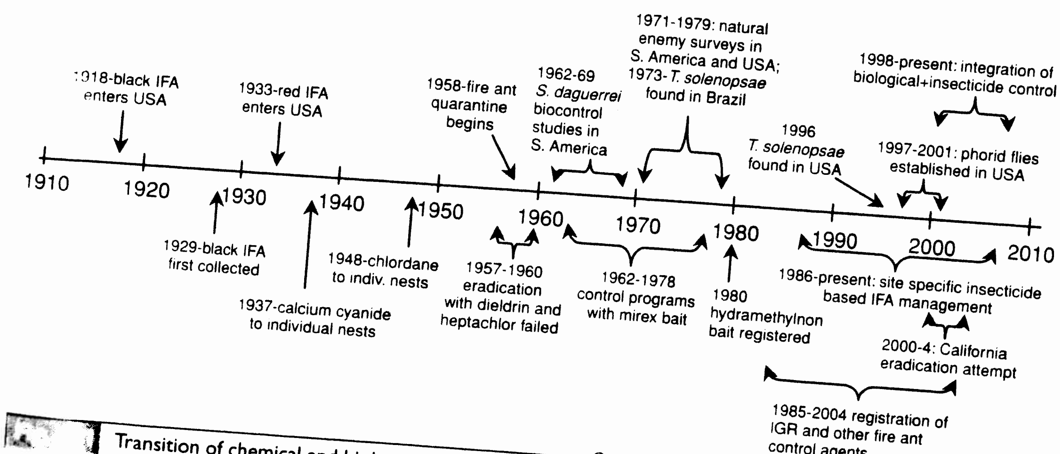
30.2 Fire ant biology and IPM

With the early emphasis on fire ant eradication, research focused on identifying effective

Table 30.1 Acute toxicity (LD_{50}[a]) of active ingredients used in formulations or products to control fire ants before and after large-scale eradication and control programs ended in the southern USA in 1978

1937–1978		1980–present	
Active ingredient	LD_{50} (mg/kg)	Active ingredient	LD_{50} (mg/kg)[b]
Calcium cyanide	39[c]	Hydramethylnon	1146
Chlordane	137–590[d]	Fenoxycarb	16 800
Dieldrin	51–64[e]	Abamectin	10[f]
Heptachlor	70–230[d]	Methoprene	> 34 600
Mirex	365–600[d]	Pyriproxyfen	>5000
		Spinosad	>5000
		Fipronil	95[f]
		Indoxacarb	1730

[a] LD_{50}, amount (mg) of technical active ingredient (AI) per kg of body weight that kills 50% of rats given the AI orally. LD_{50} of formulated products may be much higher (less toxic) than AI alone.
[b] LD_{50}s from Barr *et al.* (2005).
[c] LD_{50} from Pesticide Action Network (www.pesticideinfo.org/Index.html).
[d] LD_{50}s from Agency of Toxic Substances and Disease Registry (ATSDR) (www.atsdr.cdc.gov/toxpro2.html#bookmark05).
[e] LD_{50} from St. Omer (1970).
[f] LD_{50} from http://extoxnet.orst.edu/pips/abamecti.htm; LD_{50} of formulated fire ant products > 5000 mg/kg



Transition of chemical and biological fire ant control measures in the USA. Year active ingredients registered for fire ant control: 1985 fenoxycarb (IGR), 1986 abamectin, 1998 s-methoprene (IGR) and pyriproxyfen (IGR), 2000 spinosad and fipronil, 2004 indoxacarb.

insecticides and formulations, application rates and application technology. In addition, aspects of the biology and ecology of fire ants were also documented, and over the years the red imported fire ant has become the most studied ant species. Within the framework of IPM certain aspects of the biology and ecology of the pest must be known if environmentally compatible control tactics are to be developed and utilized effectively. Required components of IPM include basic biological information on a pest's life cycle, seasonal phenology and population dynamics. Techniques are also needed to feasibly gather the aforementioned information that are relevant and timely to manage the pest.

Identification of the pest species is one of the most basic and critical components of IPM. In the case of fire ants, species identification and nomenclature can be problematic. The name "fire ant" is most commonly used in reference to the red imported fire ant (*S. invicta*). However, "fire ant" also applies to other species in the genus *Solenopsis* (Taber, 2000) and "imported fire ant" is also used in reference to the black imported fire ant (*S. richteri*). Both of these species were accidentally introduced separately from South America into the USA before 1935 and at the time were considered to be two forms of the same species, *Solenopsis saevissima richteri*. It was not until 1972 that the two forms were formally named as separate species. Of the two species, red imported fire ant is more widespread, with black imported fire ant restricted to northern pockets in the states of Mississippi, Alabama and portions of Tennessee. In areas where the species overlap, they have hybridized. The majority of research and control efforts are for red imported fire ant, and most control recommendations are applied to both species and the hybrid. Distinguishing fire ants among each other and from other ants generally requires training. Thus, with an incursion into a new geographic area, initial detection of red imported fire ant often occurs after an infestation had established and spread. Such has been the case with the discoveries of red imported fire ant in California in 1997, New Mexico in 1998, Australia in 2001, Taiwan in 2003 and in 2005 Hong Kong, mainland China and Mexico.

The life cycle, behavior, seasonal development and other biological aspects of red imported fire ant have been examined intensively and provide a foundation for fire ant IPM and an understanding of the characteristics of a dominant invasive species. A brief overview of the biology of red imported fire ant is provided below.

Like all ants, fire ants are social insects that live in colonies and display the following characteristics: (1) cooperative brood care, where immature ants are tended by groups of adult worker ants that are not their parents; (2) overlapping generations, where at least two different generations of adults occur simultaneously in the same colony; and (3) reproductive and non-reproductive castes, where only the reproductives are capable of producing fertile offspring. The non-reproductives, or workers, perform tasks necessary for colony survival, such as foraging for food, caring for immature ants and reproductives, colony defense and nest building.

Communication needed to coordinate the activities within a colony is mediated by chemical signals called pheromones. Some of the behaviors regulated by pheromones include queen recognition and trail-following, or recruitment to a food source. Chemical cues also are used in the recognition of colony nest mates and play a role in aggression and establishing territorial boundaries between colonies. Understanding the chemical communication among fire ants can lead to novel methods of control if communication can be disrupted or to improvement of insecticidal baits by making them attractive more specifically to red imported fire ant and less available or acceptable to non-target ants. Research on such pheromones and their applications is currently in progress.

Fire ants develop from eggs, through four stages of larvae, to pupae, and finally to adults. Depending on temperature, red imported fire ant development time from egg to adult ranges from 20 to 45 days. Adult workers can live as long as 97 weeks, but depending on size and temperature, lifespans range from 10 to 70 weeks. Queens can live as long as five to seven years with maximum egg-laying rates of over 2000 eggs per day. Thus, red imported fire ant colonies can survive for several years. With the large reproductive capacity of the queen, control methods that kill workers only and do not affect the queen generally result in colony recovery.

Mature red imported fire ant colonies also contain a reproductive caste of non-stinging, winged (alate) males and females that will initiate new colonies. Alates will fly from the nest and mate in midair usually in late spring and early summer. These mated females, or newly mated queens, have been reported to fly as far as 19.3 km from the nest, or even farther when aided by wind, but most land within 1.6 km of their nest. After landing, newly mated queens move to a protected, moist harborage (e.g. in soil or crevices, under debris) that can serve as an initial nesting site. Males die after mating. A queen sheds her wings after landing, and lays a clutch of eggs which she will tend until they develop into adult workers. Worker ants will then tend the queen and the additional eggs she lays and eventually a colony can grow exponentially. After six weeks a new nest may be barely noticeable, after six months nests are typically 5 to 13 cm in diameter and detected more easily. Very large, mature colonies, that are a few years old, can construct nests over a 0.9 m in basal diameter and 0.9 m high. Over 4500 alates can be produced annually in large colonies, but it is speculated that fewer than 0.1% of the newly-mated queens will successfully found a colony (Taber, 2000). Nevertheless, enough queens will survive and can quickly reinfest treated or disturbed areas cleared of ants.

Colonies of red imported fire ant consist of two types: (1) colonies with only a single, fertile queen called monogyne colonies and (2) colonies with multiple fertile queens known as polygyne colonies. Monogyne colonies are territorial and their workers fight with other red imported fire ant colonies. As a result of this antagonistic behavior, nests are farther apart with densities of 99 to 370 nests per hectare, with 100 000–240 000 ants per colony. In contrast, polygyne colonies are not antagonistic to other polygyne colonies and thus queens, workers and immature ants (brood) can move between nests. The visible mound structure of polygyne nests are usually smaller in size and closer together than monogyne mounds with densities of 494 to 1976 per hectare, and 100 000–500 000 ants per mature colony. Polygyne populations contain nearly twice the number of worker ants per unit area than monogyne populations (35 million versus 18 million per ha). The behavioral and population size differences between monogyne and polygyne red imported fire ants can affect the type of control approach. For example, the spread of insect growth regulator baits among colonies may be greater in polygyne populations since they are not territorial. Distinguishing between the monogyne and polygyne colonies without locating fertile queens can now be accomplished through molecular markers. This has allowed for the elucidation of differential responses to control tactics between the two forms. One example is that disease may spread more rapidly in polygyne populations since ants move among colonies.

Given adequate warmth and moisture, the tremendous reproductive capacity, mobility and stinging capability, red imported fire ant has become a dominant arthropod in the areas it invaded. Red imported fire ant colonies can survive and reproduce over a temperature range of 20 to 35 °C, with optimal temperatures of 27 to 32 °C. Moisture is critical for red imported fire ant survival, where a minimum 510 mm of annual precipitation has been estimated to be a reasonable threshold for limiting colony establishment. Because colonies are very mobile and capable of relocating within a day, red imported fire ant can occupy seemingly inhospitable habitats by moving to more favorable niches as environmental conditions change.

While the knowledgebase on red imported fire ant biology and ecology is sizeable, population monitoring methods that are convenient, accurate and timely are not well developed. Traditional population assessments were designed for research studies and often entailed intensive surveys for nests and estimates of colony size based on visual rating scales, nest volume or ant activity. A simplified method of assessing red imported fire ant populations uses food lures to survey for the presence or absence of fire ants (Porter & Tschinkel, 1987; Drees, 1994; Vander Meer *et al.*, 2007). Long-range, pheromone-based surveillance traps used for other insect pests are currently not available for fire ants.

30.3 Control strategies for fire ants

30.3.1 Biological control of fire ants

Classical biological control, that is the release, establishment and spread of effective natural enemies of a pest, is one approach that offers the possibility for permanent regional suppression of fire ants. The introduction of exotic species into new continents often occurs without natural enemies. For the red imported fire ants, over 35 natural enemies have been identified in South America (Williams *et al.*, 2003) compared to about seven in the USA (Collins & Markin, 1971; Valles *et al.*, 2004). The absence of natural enemies can allow exotic species to attain much higher population densities in newly invaded regions than in their native homelands. Accordingly, fire ant populations in the USA generally are five to ten times higher than in South America (Porter *et al.*, 1997).

Interest in natural enemies of both red imported fire ant and black imported fire ant extended back into the era of the mirex control programs. In the 1960s Silveira-Guido *et al.* (1973) conducted extensive studies on the parasitic ant *Solenopsis (Labauchena) daguerrei* which was found on several species of *Solenopsis* fire ants in South America. Other parasites, such as *Pseudacteon* phorid flies and *Orasema* eucharitid wasps, have been reported from fire ants. Surveys for pathogens of fire ants in South America and the southeastern USA have been conducted since the 1970s with several microorganisms being evaluated as biological control agents (Williams *et al.*, 2003).

To date, two microsporidian pathogens (*Thelohania solenopsae* and *Vairimorpha invictae*) have proven to be most detrimental to fire ant colonies in the field. *Thelohania solenopsae* (recently placed in genus *Kneallhazia*: Sokolova & Fuxa, 2008) caused reductions of up to 83% in field populations of black imported fire ants in Argentina. This organism was discovered in the USA in 1996 and has since been found or introduced in several states. Infections of red imported fire ant have resulted in population reductions of 63% and smaller nest sizes in the USA. In addition, *T. solenopsae* infected fire ant colonies were more susceptible to fire ant bait than uninfected colonies. *Vairimorpha invictae* infections alone and in combination with *T. solenopsae* have resulted in dramatic declines (53–100%) in red imported fire ant populations in Argentina (Briano, 2005). *Vairimorpha invictae* is currently being evaluated for release in the USA.

In 1997, the first successful releases were made of a phorid fly (*Pseudacteon tricuspis*) which parasitizes and eventually decapitates fire ants. Another phorid fly (*Pseudacteon curvatus*) has since been released and established in the USA on both black imported fire ant and red imported fire ant. Direct mortality of individual fire ants through parasitism by *P. tricuspis* was found to be <1%, but the main phorid fly impact is thought to be indirect. For example, it is well documented that the presence of phorid flies disrupts normal foraging behavior (Porter, 1998). In laboratory studies deleterious impacts on colonies by foraging disruption have been inconsistent and influenced by the experimental designs. An extensive field study in Florida could not detect reductions in fire ant populations by *P. tricuspis* relative to natural fluctuations in fire ant populations (Morrison & Porter, 2005). All the above studies caution that detection of fire ant population reductions by phorids may require more species and time.

30.3.2 IPM of fire ants

IPM for imported fire ants includes utilizing cultural, biological and chemical control methods or their combination. In contrast to the concept of treating entire counties or states for fire ant eradication as discussed earlier, fire ant IPM entails site-specific, goal-oriented management programs for commonly infested sites. Current approaches to manage imported fire ants were described in state extension service bulletins (Flanders & Drees, 2004; Drees *et al.*, 2006). The goal of these programs was to prevent or eliminate problems caused by fire ants for a specific land-use pattern rather than elimination of all ants from the ecosystem. Certainly, doing nothing is recognized as one option, especially where the potential for being stung is minimal due to the lack of human or fire ant activity. Predominately shaded and/or dry habitats are unfavorable to fire ant colonization and may not require treatment. Where fire ant suppression is desired, justified use of insecticides has remained the primary tactic for control. Because fire ant baits generally need to be fed upon within a day before they degrade, timing bait applications relative to active foraging can improve control. Development of additional insecticide products that are more cost-effective, target-specific and safer to the user and the environment will continue to improve fire ant IPM.

Control in urban areas

Because of the fire ant's aggressive stinging behavior, fire ant control programs have been developed for specific urban areas such as lawns and athletic fields, buildings, electrical equipment, vegetable gardens, flower beds and shorelines. Each of these areas is often frequented by people and pets and represents different situations that may require different treatment regimes. In lawns and athletics fields where there is a low tolerance for fire ants (a primary habitat of fire ants that is frequented by people), three main treatment approaches, or programs, have been described:

PROGRAM 1: "TWO-STEP METHOD"

This program used the broadcast application of a bait formulated product (step 1), followed by treating nuisance ant nests with an individual nest treatment (step 2). This has been the least-toxic, most environmentally sound approach for treating heavily infested medium-sized to large areas (Riggs *et al.*, 2002; Drees, 2003). However, it was not suggested for use in previously untreated areas with few fire ant nests (≤8 nests/ha), or where competitor ant species were to be preserved. The goal of this program was to reduce fire ant problems while minimizing the search and treatment of individual nests. Because most bait products take at least two weeks to kill colonies, only nuisance nests were individually treated with fast-acting insecticides that kill ants on contact. With the development of fire ant baits that can eliminate colonies within a few days, treatment of individual nests (step 2) may be unnecessary if fast-acting baits are broadcast in step 1.

PROGRAM 2: INDIVIDUAL NEST TREATMENTS

This approach was best used in small areas (usually 0.4 ha or less) with fewer than 8 to 12 nests per ha or where preservation of native ants was desired. This program selectively treated fire ants by targeting only their nests, but rapid reinvasion was anticipated from undetected or untreated colonies in surrounding areas (Barr *et al.*, 1999). Individual nest treatments included insecticides applied as dusts, granules, granules drenched with water after application, liquid drenches, baits, or aerosol injections. Non-chemical treatment methods such as drenching nests with hot water also could be used.

PROGRAM 3: LONG-RESIDUAL CONTACT INSECTICIDE TREATMENT

This program used a long-residual contact insecticide applied to the soil surface (Drees *et al.*, 2006). These liquid or granular treatments could kill a greater number of other ants besides fire ants. Its effects could be more rapid than the other programs and reinvasion of treated areas by migrating colonies and newly mated queen ants was minimized as long as the insecticide remained active.

PROGRAM COMBINATIONS

Any of the three programs above could be used on specific sites within a managed area where different levels of fire ant control were desired. On golf courses, for instance, Program 3 could be suitable for high use areas such as putting greens and tee boxes. In fairways and rough areas, Program 1 could be sufficient.

Control in agricultural production systems

In commercial agriculture, justified treatment costs would be less or equal to the losses sustained by fire ants. In cattle operations the estimated cost for treatments using broadcast application of conventional fire ant baits in pastures is approximately $US 25/ha. For small operations this treatment cost may be negligible, while in larger operations, this treatment cost may be unacceptably high. With the exception of a few, most fire ant baits have not been approved for all use sites that comprise a cattle operation. In these situations, a better approach to treating the entire ranch with one bait product would be the implementation of site-specific IPM techniques that include chemical as well as cultural methods. For example, bait could be applied only to a designated calving pasture and calving programs could be scheduled to avoid summer months when fire ant activity is high. Few fire ant baits have been registered for use in food crops, thus limiting control options in crop production systems. It should be noted that since fire ants are major predators of arthropods, they are beneficial in some systems (e.g. sugarcane) by significantly reducing pest populations.

Community-wide and areawide fire ant management and abatement programs

Although site-specific IPM approaches have been widely promoted for use on individual properties, reinvasion by the ants from neighboring untreated areas has been a recurring problem. By treating larger outdoor areas (i.e. entire neighborhoods), reinfestation has been shown to be reduced. Beginning in 1993, demonstrations of community treatments were reported from Alabama and Arkansas. Benefits from community-wide fire ant management in Texas included reductions in fire ant populations, less pesticide expenditures by homeowners and the maintenance or increases in other ant species (Riggs *et al.*, 2002). All of these programs have relied on aerial or ground broadcast application of bait-formulated insecticides as well as sustained community leadership and involvement.

Integration of biological control agents with chemical control programs

Efforts have been made to demonstrate the impact of integrating classical biological control agents with insecticide applications for fire ant control. The objective of releasing natural enemies of fire ants is to establish self-sustaining suppression of imported fire ant populations. However, the reduction in fire ant populations after establishment and spread of the phorid fly *P. tricuspis* or the fire ant pathogen *T. solenopsae* has not been sufficient to alleviate the threat of fire ant stings to tolerable levels. However, when biological controls were established in unmanaged landscapes surrounding areas chemically treated for fire ants, control was extended in the treated areas by over a year (Oi *et al.*, 2008). It is hypothesized that the establishment of several parasites and pathogens of fire ants will, over time, help reduce sources of fire ant reinfestations into managed landscapes or sensitive areas such as playgrounds. Thus, insecticide use for fire ants may be reduced.

30.4 Eradication programs in southern California and Brisbane, Australia

As discussed previously, attempts to eradicate fire ants from 1957 through 1977 failed to eliminate these species from the southeastern USA. By the mid-1980s, the concept of eradicating the fire ants from the southeast had been abandoned. Nevertheless, many small isolated infestations have routinely been eradicated by state department of agriculture personnel throughout the USA and the USDA-Animal Plant Health Inspection Service has maintained an imported fire ant quarantine. Few, if any, of these successful efforts have been documented in the scientific literature. The development of fire ant baits that contain insect growth regulating (IGR) active ingredients, e.g. fenoxycarb, methoprene and pyriproxyfen, have provided more tools for treating large land areas. IGR baits have fewer environmental impact concerns, and some are registered for use in a broader range of land-use patterns, including cropland. In addition, the availability of global positioning and geographic information systems have facilitated delineation and treatment of infested areas.

In 2000 and 2001, eradication programs were implemented in southern California, USA and in Brisbane, Australia, respectively. Both programs were designed, in part, on considerations for spot eradication, suggesting that infestations be surveyed so that, where feasible and justifiable, insecticide treatments be made to the entire population including a buffer area where fire ants were not detected. Suggested treatments included a minimum of two broadcast bait applications annually for several years with IGR baits to prevent further spread (Drees *et al.*, 2000). Winged female reproductive caste ants produced in IGR treated colonies do not have functional ovaries, inhibiting spread by mating flights. Aerial treatment was encouraged to attain thorough coverage in a timely manner, but only ground application was used in urbanized areas in both programs. Additional treatments using bait or individual nest treatments with faster modes of action could hasten population reduction. Finally, program success could be documented through several years of intensive ant surveys in and around previously treated areas.

In southern California, after the initial discovery of fire ants in October 1998, the California Department of Food and Agriculture delineated the infestation and issued proclamations of eradication in three counties encompassing over 204 000 ha. Local county agencies were then contracted to survey for ants and conduct large-scale broadcast application of fire ant baits primarily containing pyriproxyfen or hydramethylnon. The program made applications from February 2000 through February 2004, treating over 29 000 sites in one county alone. The treatments were made to most properties four times per year at three- to four-month intervals. Post-treatment monitoring began three months after the final treatment and showed fewer than 5% of the sites remained infested. However, because of budget reductions, the eradication effort was terminated in February 2004. Since then residents from two counties voted to approve a new program initiated in October 2004 to complete treatments and surveys in parks, school greenbelts, public medians and commercial businesses. Nevertheless, eradication has not been achieved because not all infested areas were treated or received the full treatment regime.

In Brisbane, Australia, the eradication program was initiated by the Queensland Department of Primary Industries and the Fire Ant Control Centre (FACC) in 2001, within a year of confirming the infestation of over 37 000 ha. The eradication program involved three years of multiple annual treatments (broadcasting pyriproxyfen, hydramethylnon or methoprene baits; and nest injection of chlorpyrifos or fipronil), followed by two years of surveillance. From 2001 through 2006 additional detections expanded the program significantly and additional treatment areas and surveillance was required through 2007. In 2006, the program included 62 250 ha under surveillance following treatment and 6200 ha still under treatment. Treatment using aerial application was made to non-urbanized lands where use of insecticides was permitted, including land bordering bodies of water. Scheduling ground treatments using vehicle-mounted or hand-held application equipment and surveillance using visual inspections and ground traps for such a large infested area was obviously challenging, but most likely was facilitated by having a well-funded, single, centralized authority to direct and implement operations. Results from this large program have been very promising. In 2006, only about 150 red imported fire ant colonies were found in 49 properties of 160 000 in the treated area, an infestation rate of about 0.03%. The impressive eradication effort in Australia benefited from high public support and secure funding.

The major problem with documenting successful eradication is to find and eliminate the last fire ant colony. Surveillance for two (or more) years following termination of prescribed treatments may still fail to detect low numbers of surviving colonies. Utilizing computer modeling with satellite imagery to locate favorable fire ant habitats has made surveillance more efficient, yet improvements in detecting fire ants at very low population densities are a critical need. New incursions could be occurring unless vigilance at ports and other points of commerce is maintained. Systematic surveillance and rapid responses have limited incursions in New Zealand. Only time will confirm whether these eradication efforts have truly been successful.

30.5 Conclusions

In summary, the rapid and extensive spread of the easily recognized, stinging fire ant into the southern USA provoked drastic attempts to eliminate or control the problem quickly. Unfortunately, fire ants, with their tremendous reproductive capacity, mobility and adaptation to a wide range of habitats made eradication, especially without a thorough understanding of their biology and ecology, highly unlikely. With eradication in the southern USA no longer an option, greater emphasis was placed on basic biological research which ultimately improved control measures including the utilization of biological control. With the expansion of global commerce, extensive fire ant infestations have occurred in Australia and Asia and new incursions will certainly continue. The fire ant invasion of the USA has provided valuable lessons, technology and knowledge on fire ant control and biology. This has provided a basis for the ongoing development of fire ant IPM as well as recent eradication programs. Furthermore the fire ant experience can serve as a blueprint from which informed decisions and responses can be formulated for other invasive ant species.

References

Banks, W. A., Glancey, B. M., Stringer, C. E. *et al.* (1973). Imported fire ants: eradication trials with mirex bait. *Journal of Economic Entomology*, **66**, 785–789.

Barr, C. L., Summerlin, W. & Drees, B. M. (1999). A cost/efficacy comparison of individual mound treatments and broadcast baits. In *Proceedings of* *the 1999 Imported Fire Ant Conference*, March 3–5, Charleston, SC, pp. 31–36. Clemson, SC: Clemson University Cooperative Extension Service.

Barr, C. L., Davis, T., Flanders, K. *et al.* (2005). *Broadcast Baits for Fire Ant Control, B-6099*. College Station, TX: Texas Cooperative Extension, Texas A&M University System.

Briano, J. A. (2005). Long-term studies of the red imported fire ant, *Solenopsis invicta*, infected with the microsporidia *Vairimorpha invictae* and *Thelohania solenopsae* in Argentina. *Environmental Entomology*, **34**, 124–132.

Canter, L. W. (1981). *Final Programmatic Environmental Impact Statement for the Cooperative Imported Fire Ant Program*. ADM-81-01-F. Washington, DC: US Department of Agriculture, Animal Plant Health Inspection Service.

Carson, R. (1962). *Silent Spring*. Boston, MA: Houghton Mifflin.

Collins, H. L. & Markin, G. P. (1971). Inquilines and other arthropods collected from nests of the imported fire ant, *Solenopsis saevissima richteri*. *Annals of the Entomological Society of America*, **64**, 1376–1380.

Drees, B. M. (1994). Red imported fire ant predation on nestlings of colonial waterbirds. *Southwestern Entomologist*, **19**, 355–360.

Drees, B. M. (2003). *Estimated Amounts of Insecticide Ingredients Used for Imported Fire Ant Control Using Various Treatment Approaches*, Fire Ant Plan Fact Sheet No. FAPFS042. College Station, TX: Texas Imported Fire Ant Research & Management Project, Texas A&M University System.

Drees, B. M., Collins, H., Williams, D. F. & Bhatkar, A. (2000). *Considerations for Planning, Implementing and Evaluating a Spot-Eradication Program for Imported Fire Ants*, Fire Ant Plan Fact Sheet No. FAPFS030. College Station, TX: Texas Imported Fire Ant Research & Management Project, Texas A&M University System.

Drees, B. M., Vinson, S. B., Gold, R. E. *et al.* (2006). *Managing Imported Fire Ants in Urban Areas, a Regional Publication Developed for: Alabama, Arkansas, California, Florida, Georgia, Louisiana, Mississippi, New Mexico, Oklahoma, South Carolina, Tennessee and Texas, B-6043*. College Station, TX: Texas Cooperative Extension, Texas A&M University.

Flanders, K. L. & Drees, B. M. (2004). *Management of Imported Fire Ants in Cattle Production Systems*, ANR-1248. Auburn, AL: Alabama Cooperative Extension System.

Jetter, K. M., Hamilton, J. & Klotz, J. H. (2002). Red imported fire ants threaten agriculture, wildlife, and homes. *California Agriculture*, **56**, 26–34.

Lofgren, C. S. (1986). History of the imported fire ants in the United States. In *Fire Ants and Leaf-Cutting Ants: Biology and Management*, eds. C. S. Lofgren & R. K. Vander Meer, pp. 36–47. Boulder, CO: Westview Press.

Lofgren, C. S. & Weidhaas, D. E. (1972). On the eradication of imported fire ants: a theoretical appraisal. *Bulletin of the Entomological Society of America*, **18**, 17–20.

Lofgren, C. S., Bartlett, F. J. & Stringer, C. E. (1963). Imported fire ant toxic bait studies: evaluation of carriers for oil baits. *Journal of Economic Entomology*, **56**, 62–66.

Markin, G. P., O'Neal, J. & Collins, H. L. (1974). Effects of mirex on the general ant fauna of a treated area in Louisiana. *Environmental Entomology*, **3**, 895–898.

McNicol, C. (2006). Surveillance methodologies used within Australia: various methods including visual surveillance and extraordinary detections – above ground and in ground lures. In *Proceedings of the Red Imported Fire Ant Conference*, March 28–30, 2006, Mobile, AL, ed. L. C. Graham, pp. 69–73. Auburn, AL: Department of Entomology and Plant Pathology, Auburn University.

Morrison, L. W. & Porter, S. D. (2005). Testing for population-level impacts of introduced *Pseudacteon tricuspis* flies, phorid parasitoids of *Solenopsis invicta* fire ants. *Biological Control*, **33**, 9–19.

Oi, D. H. & Oi, F. M. (2006). Speed of efficacy and delayed toxicity characteristics of fast-acting fire ant (Hymenoptera: Formicidae) baits. *Journal of Economic Entomology*, **99**, 1739–1748.

Oi, D. H., Williams, D. F., Pereira, R. M., *et al.* (2008). Combining biological and chemical controls for the management of red imported fire ants (Hymenoptera: Formicidae). *American Entomologist*, **54**, 46–55.

Porter, S. D. (1998). Biology and behavior of *Pseudacteon* decapitating flies (Diptera: Phoridae) that parasitize *Solenopsis* fire ants (Hymenoptera: Formicidae). *Florida Entomologist*, **81**, 292–309.

Porter, S. D. & Tschinkel, W. R. (1987). Foraging in *Solenopsis invicta* (Hymenoptera: Formicidae): effects of weather and season. *Environmental Entomology*, **16**, 802–808.

Porter, S. D., Williams, D. F., Patterson, R. S. & Fowler, H. G. (1997). Intercontinental differences in the abundance of *Solenopsis* fire ants (Hymenoptera: Formicidae): escape from natural enemies? *Environmental Entomology*, **26**, 373–384.

Riggs, N. L., Lennon, L., Barr, C. L. *et al.* (2002). Community-wide red imported fire ant programs in Texas. *Southwestern Entomologist* (Suppl.) **25**, 31–42.

Silveira-Guido, A., Carbonell, J. & Crisci, C. (1973). Animals associated with the *Solenopsis* (fire ants) complex, with special reference to *Labauchena daguerrei*. *Proceedings of the Tall Timbers Conference on Ecological Animal Control by Habitat Management*, **4**, 41–52.

Sokolova, Y. Y. & Fuxa, J. R. (2008). Biology and life-cycle of the microsporidium *Kneallhazia solenopsae* Knell Allan Hazard 1977 gen. n., comb. n., from the fire ant *Solenopsis invicta*. *Parasitology*, **135**, 903–929.

St. Omer, V. V. (1970). Chronic and acute toxicity of the chlorinated hydrocarbon insecticides in mammals and birds. *Canadian Veterinary Journal*, **11**, 215–226.

Taber, S. W. (2000). *Fire Ants*. College Station, TX: Texas A&M University Press.

Tschinkel, W. R. (2006). *The Fire Ants*. Cambridge, MA: Belknap Press of Harvard University Press.

Valles, S. M., Strong, C. A., Dang, P. M. *et al.* (2004). A picorna-like virus from the red imported fire ant, *Solenopsis invicta*: initial discovery, genome sequence, and characterization. *Virology*, **328**, 151–157.

Vander Meer, R. K., Pereira, R. M., Porter, S. D., Valles, S. M., & Oi, D. H., (2007). Areawide suppression of invasive fire ant populations. In *Area-Wide Control of Insect Pests: From Research to Field Implementation*, eds. M. J. B. Vreysen, A. S. Robinson & J. Hendrichs, pp. 487–496. Dordrecht, Netherlands: Springer-Verlag.

Williams, D. F., Collins, H. L. & Oi, D. H. (2001). The red imported fire ant (Hymenoptera: Formicidae): a historical perspective of treatment programs and the development of chemical baits for control. *American Entomologist*, **47**, 146–159.

Williams, D. F., Oi, D. H., Porter, S. D., Pereira, R. M. & Briano, J. A. (2003). Biological control of imported fire ants (Hymenoptera: Formicidae). *American Entomologist*, **49**, 150–163.

Wojcik, D. P., Allen, C. R., Brenner, R. J. *et al.* (2001). Red imported fire ants: impact on biodiversity. *American Entomologist*, **47**, 16–23.