CHAPTER 25

Biological Control of Invasive Mole Crickets in Florida

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NON-TECHNICAL SUMMARY

Neoscapteriscus (Orthoptera: Gryllotalpidae) mole crickets from southern South America arrived in Georgia and Florida from 1899 to the 1920s in dry ship ballast. Over time, they built up huge populations and were targeted for control with many toxic pesticides. In the 1970s, the U.S. Environmental Protection Agency banned the use of one of these pesticides, chlordane, which southeastern ranchers had come to use extensively for mole cricket suppression. Lacking this pesticide, the ranchers asked for help against these invasive mole crickets, which led to the creation of a mole cricket research program at the University of Florida.

Trapping stations were established in 1979 to catch mole crickets so their numbers could be monitored, and while each trap caught thousands of flying mole crickets each year, trapping was unable to reduce mole cricket populations. The lowest-cost control method that researchers could envisage was classical biological control, which, if successful, would provide permanent control without recurrent costs for ranchers. To begin this process, rearing methods were developed for the mole crickets, so that they would be available for experimentation.

In South America, surveys for specialized mole cricket natural enemies found a species of tachinid fly, a crabronid wasp, an entomopathogenic nematode, and a bombardier beetle, each with interesting but incompletely known life histories. Stocks of these four organisms were brought into a quarantine laboratory in Florida, and studies showed that three of the four were proven to be safe to the Florida environment, people, and non-target insects. The three were reared in large numbers and released, starting in 1985.

By fall of 1990, mole cricket numbers began to decline, and by 2000, the average catch in monitoring traps was only 5% of the numbers seen during the 1980s, a permanent 95% reduction of the scope of the problem with no annual recurring costs. Since the conclusion of the research program in 2004, these natural enemies have continued to spread, and they should continue to reduce damage throughout Florida in organic vegetables, pastures, turf, and playing fields, wherever climates are suitable. The program's benefit:cost ratio was 52:1, meaning that the benefits to the public are at least 52 times larger than all the funds expended on the program.

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HISTORY OF INVASION AND NATURE OF PROBLEM

The Species Invasion

In the late 1890s, invasive mole crickets were detected in Georgia, and then in Florida. They were not the familiar but harmless native northern mole cricket, *Neocurtilla hexadactyla*, but a species in the genus *Neoscapteriscus*, and it was associated with damage in various vegetable crops (cabbage, green peppers, eggplant, etc.). Initially, these pests were thought to be the West Indian mole cricket, *Neoscapteriscus didactylus*, a pest mole cricket known in Puerto Rico and some other Caribbean Islands.

Eventually, insect taxonomists determined that the mole crickets represented three invasive species, which are now called (1) tawny mole cricket, *Neoscapteriscus vicinus*, (2) short-winged mole cricket, *Neoscapteriscus abbreviatus*, and (3) southern mole cricket, *Neoscapteriscus borellii* (all Orthoptera: Gryllotalpidae). The arrival of these insects was in Brunswick, Georgia, which at the time was a major seaport shipping goods to and from southern South America (Argentina and Uruguay) where all three species are native. It was deduced that these crickets had arrived in ship ballast (Walker and Nickle, 1981). These mole crickets in their native ranges are frequently found along riverbanks, where they could easily be included in sand and gravel dug and used as ballast in ships bound to the southern United States.

Adults of two of the species (tawny and southern) fly readily in spring and fall and spread from Florida to North Carolina and west to Texas. Undoubtedly the southern mole cricket also hitchhiked on vehicles to reach extreme western Arizona, a site in northern Mexico, and California. Short-winged adults cannot fly and are restricted to the eastern and southwestern coasts of Florida with very few inland sites.

Nature of the Problem

For some years, mole cricket damage occurred mainly in vegetable crops, caused by feeding of nymphs and adults on plant roots or stems. In the 1930s, growers tried to control these losses with soil applications of calcium and potassium arsenates. In 1940, Florida growers appealed for federal help, and 1,258 tons of calcium arsenate bran bait were donated to Florida growers in the worst affected counties. In the mid to late 1940s, synthetic chemical pesticides were first developed, starting with the chlorinated hydrocarbons such as DDT. The chlorinated hydrocarbon chlordane provided excellent control of mole crickets, and it was widely adopted for that purpose, not only in vegetable fields, but also on playing fields and pastures where Bermudagrass (*Cynodon dactylon*) and Bahiagrass (*Paspalum notatum*) roots were being heavily damaged. Mole cricket tunneling loosens the roots of grass, and affected pasture grasses die when cattle subsequently uproot them. Use of chlordane on playgrounds and pastures prevented such devastating losses from pest mole crickets. However, chlordane, like DDT, was eventually banned from use in agriculture because its long-lasting residues polluted habitats, leaving toxins that affected wildlife and people's health. In short, this management approach was initially highly effective but was unsustainable because of the pollution it caused.

WHY CONTROL THESE INVASIVE SPECIES?

The control of mole crickets was justified because of the value to the state and nation of the products produced on Florida pastures, which have been important for raising of beef cattle since at least the 1860s. Currently, most cattle operations in Florida are cow-calf businesses with mature calves being shipped to other states for finishing and processing. In 2007, 450,000 cows worth about $400 million were processed. At that time in Florida, beef was produced on 3.2 million acres (1.2 million ha) of pasture land and 1.3 million acres (0.5 million ha) of grazed woodland which was just over 10% of the state.

The need for a biological control project was triggered in pastures in 1978, when the use of chlordane was banned by the U.S. Environmental Protection Agency, because no other chemical insecticides were so effective and inexpensive for killing pest mole crickets. Florida ranchers requested help from the Florida Legislature, which earmarked research funds for this purpose. These funds supported work at the University of Florida Department of Entomology and Nematology, which first carried out the necessary research and then implemented the biocontrol program.

PROJECT HISTORY THROUGH AGENT ESTABLISHMENT

This program ultimately involved the release of three agents—the wasp *Larra bicolor* (Hymenoptera: Crabronidae), the nematode *Steinernema scapterisci* (Rhabditida: Steinernematidae), and the parasitic fly *Ormia depleta* (Diptera: Tachinidae)—against three species of invasive mole crickets: tawny mole cricket, *N. vicinus*, short-winged mole cricket, *N. abbreviatus* (**Fig. 1**), and southern mole cricket, *N. borellii*. The names for these species and other associated species have changed over time and are summarized in **Table 1** for easy reference.

Figure 1. Adult short-winged mole cricket, *Neoscapteriscus abbreviatus.* (Paul Choate, University of Florida)

The program first concentrated on understanding the feeding habits of the three invasive mole crickets, which vary. Tawny mole crickets and short-winged mole crickets feed almost entirely on plants, but southern mole crickets are mainly predatory, though they are also destructive to grasses.

Studies were also conducted on the male crickets' songs, which are species-specific and attract the flying females. Electronic sound-emitting devices were built that exactly replicated the songs of tawny mole cricket or southern mole cricket. This was not done for short-winged mole crickets because they neither sing nor fly. When these sound emitters were built into funnel-shaped traps (**Fig. 2**), it made for an effective trap to collect the flying female mole crickets, which allowed researchers to monitor the size of cricket populations (Walker, 1982).

Figure 2. Sound emitter for attracting long-winged mole crickets (they fall into the bucket below) and *Ormia depleta* flies (they move into the transparent vial at top). (Lyle Buss, University of Florida)

Early on, a new, very low-cost insecticide bait to kill mole crickets was developed that combined chicken feed, some additives, and 2% malathion insecticide (Kepner and Yu, 1987). The product was designed to be formulated by ranchers themselves. However, the Florida Department of Agriculture declared it unsafe because the bait might attract wild birds, and consequently it was banned. The loss of this insecticidal-bait focused attention on classical biocontrol, which was reasoned to be the lowest-cost control method in the long term.

Table 1. Names applied to the organisms in the mole cricket biocontrol program. N = native, I = invasive species, BC = biocontrol.

Common name	Earlier name	Latest name	Feeding habits	Origin (N or I)
tawny mole cricket	*Scapteriscus vicinus* Scudder	*Neoscapteriscus vicinus* (Scudder)	Feeds on plants	I
short-winged mole cricket	*Scapteriscus abbreviatus* Scudder	*Neoscapteriscus abbreviatus* (Scudder)	Feeds on plants	I
southern mole cricket	*Scapteriscus acletus* Rehn and Hebard	*Neoscapteriscus borellii* (Giglio-Tos)	Mainly predatory	I
northern mole cricket		*Neocurtilla hexadactyla* (Perty),	Mainly predatory; not damaging	N
West Indian mole cricket	*Scapteriscus didactylus* (Latreille)	*Neoscapteriscus didactylus* (Latreille)	Feeds on plants	I
None	*Larra americana* Saussure	*Larra bicolor* Fabricius	Parasitoid attacking mole crickets	BC agent
None	*Neoaplectana* sp.	*Steinernema scapterisci* Nguyen and Smart	Mole cricket nematode	BC agent
None	*Euphasiopteryx depleta* (Wiedemann)	*Ormia depleta* (Wiedemann)	Parasitoid attacking mole crickets	BC agent
(*Larra bicolor*'s best nectar plant)	*Borreria verticillata* (L.) G.F.W. Mey	*Spermacoce verticillata* L.	Nectar plant	Debated

Larra bicolor

Figure 3. Adult female *Larra bicolor* wasp attacking an adult *Neoscapteriscus vicinus.* (Lyle Buss, University of Florida)

Larra bicolor (**Fig. 3**) is a parasitic wasp that was already known at the start of the program to attack mole crickets, having been introduced earlier into Puerto Rico from Belém in the Brazilian state of Pará on the Amazon River in the late 1930s to suppress the West Indian mole cricket. However, Puerto Rican entomologists did not develop a method to evaluate this wasp's effects. Efforts to import *L. bicolor* into Florida in the 1940s were unsuccessful. A second attempt, also from Puerto Rico, was made in 1981. A population of the wasp did become established, but only at one site in Fort Lauderdale, from which it spread only slightly. The key factor in this establishment seems to have been the establishment of *Spermacoce verticillata* (Rubiaceae), a plant that produces nectar used by *L. bicolor*. This population of *L. bicolor*, however, had a negligible effect on mole crickets, killing only about 1% of the short-winged mole crickets at the site, and none of the other two species (based on the percentage of crickets in pitfall traps that had wasp eggs or larvae on them) (Castner, 1988).

A third attempt to import a population of *L. bicolor* more adapted to Florida's climate was made in 1988. As the Puerto Rican population imported in 1981 to Florida had been originally from Belém, Brazil on the equator, it may not have been sufficiently cold hardy to survive in northern Florida. So, the same wasp species was imported from Santa Cruz de la Sierra in Bolivia at 18° south latitude and 1,365 ft (416 m) altitude, which suggested that these wasps might have some tolerance to colder temperatures. These wasps became established in Gainesville, Florida (Frank et al., 1995) and then spread in northern Florida. Wasps that had developed in northern Florida were later released at Tifton, Georgia. They established and spread to Alabama and Mississippi, and then along the east coast north to coastal North Carolina. By 2008, *L. bicolor* had been recorded in 48 of Florida's 67 counties (Frank et al., 2009a).

How successful *L. bicolor* was in killing pest mole crickets in Florida was answered by graduate student S. L. Portman in a field study in north Florida (Portman et al., 2009). He found that if a population of the wasp had a convenient nectar source (a patch of a dozen or so *S. verticillata* plants within 650 ft [200 m]) of the pasture, they could out-reproduce mole crickets. Male wasps are typically seen on sunny days feeding on plant nectar, while many females were hunting mole crickets (Portman et al., 2010). Provisioning of pastures with these nectar plants is not hard for ranchers to arrange (Frank and Sourakov, 2002).

The nectar plant *S. verticillata* has been discussed as an invasive plant in Florida. However, under alternate names, this same plant was recorded from Big Pine Key in Florida in 1860 and from the vicinity of Ross Hammock in the Everglades in 1915, perhaps suggesting it is a native species. In 1990, the UF/IFAS Invasive Plant Council was petitioned for an opinion and stated that *S. verticillata* is not invasive, thus allowing the mole cricket researchers to recommend its planting as a nectar source for *L. bicolor*. Planting the species along roadsides would help promote populations of *L. bicolor*. *Spermacoce verticillata* is not toxic to vertebrates and, in fact, it is suitable for grazing by cattle. A decade later, the Florida Exotic Pest Plant Council announced that *Spermacoce verticillata* is invasive; however, weed scientists (Sellers et al., 2019) recommended against trying to eliminate it from pastures because it promotes adult survival and population growth of *L. bicolor*. This decision was based on the same rationale invoked for promoting Bahiagrass, an invasive plant, including giving it exemption from invasive regulations as it is also useful.

Steinernema scapterisci

To explore for natural enemies of mole crickets in southern South America, mole cricket researcher T. J. Walker obtained USDA funds to support a post-doctoral researcher in South America. H. G. Fowler was hired and established a base for his surveys at Rio Claro in the Brazilian state of São Paulo, which had *N. borellii* and *N. vicinus* populations and was only a few hours southwest of the coast of Rio de Janeiro, where *N. abbreviatus*, the third target species, could be obtained. From field-collected mole crickets, Fowler recovered nematodes that he shipped to Gainesville, Florida, but nematode survival was low. Dr. Aquiles Silveira-Guido, a retired professor in Uruguay, was hired to work on the project, and he too found nematodes and shipped some to Gainesville. In 1985, nematologist G. C. Smart and his student K. B. Nguyen visited Fowler and Silveira-Guido. They collected nematodes from the cultures maintained by Silveira-Guido and successfully brought samples of the newly discovered parasitic nematode back to Florida.

Among the various nematodes collected in Uruguay, there was an undescribed species of *Neoaplectana* that was later described as a new species of *Steinernema*, which proved to be highly specific to *Neoscapteriscus* mole crickets. It was named *Steinernema scapterisci* (**Fig. 4**) (Nguyen and Smart, 1990), and later, its associated bacterial symbiont was described as *Xenorhabdus innexi* (Lengyel, 2005). In this period, entomopathogenic nematodes of foreign origin had a blanket exemption from USDA regulations, being recognized as "harmless to vertebrate animals and to plants." Therefore they could be released

Figure 4. *Neoscapteriscus vicinus* with emerging *Steinernema scapterisci* juveniles. (Lyle Buss, University of Florida)

without review in the United States. Non-target tests done at the University of Florida in Gainesville showed this nematode had no effect on honeybees, but it did attack a small percentage of the non-native house cricket, *Acheta domesticus*, which does not exist outdoors in Florida.

This new nematode was reared on mole crickets that were available from field monitoring traps or laboratory rearing. The first field releases of the nematode took place in 1985 in small plots in pastures in Alachua County, Florida. Some nematodes were released by burying dead, infested mole crickets, but others were applied in water with a sprinkling can, at approximately 2.7 million per ft^2 (250,000/m^2) based on laboratory experimentation (Hudson and Nguyen, 1989). Both methods placed the nematode beneath the soil surface because such nematodes are known to be quickly killed by exposure to ultraviolet light and desiccation. Both application methods were effective in causing infections in wild mole crickets at the field sites. Mole cricket numbers in those plots were monitored for six years, during which time mole cricket numbers were observed to decline and the nematodes to persist. The plots also contained native northern mole crickets, *N. hexadactyla*, and when these were examined, they were found to be infected with a different, presumably native, nematode that was later described as *Steinernema neocurtillae* (Nguyen and Smart, 1992).

Rearing the new South American nematode at a scale sufficient for widespread release could not be done without the aid of a commercial producer of nematode products. G. C. Smart, through the University of Florida's Office of Technology Licensing, obtained a patent for use of this nematode for control of mole crickets, and Biosys, a California company in the business of mass-producing beneficial nematodes, agreed to develop mass-production methods for *S. scapterisci*. Biosys supplied enough nematodes in a water-soluble gel for trial applications on one large cattle pasture in each of six Florida counties. Nematodes were applied to the subsurface by a tractor-drawn chisel rig in fall 1989 and spring 1990 when mole crickets were adults or almost so (the most susceptible stage). Because chemical control of mole crickets targets small mole crickets in summer (Parkman et al., 1993), the effectiveness of pesticides vs. nematodes could not be directly compared. Dispersal of the nematodes outward from the 2.5-acre (1-ha) treated areas on these six ranches occurred by crawling of infected mole crickets (likely only about 200 ft [60 m] in the 21-month study) or by flight of infested adult crickets, which potentially could reach much greater distances.

In the 1990s and the first decade of the 2000s, commercial production of this nematode was undertaken by several companies and applied in various formulations with various kinds of application machinery. This occurred in two very different settings, including golf courses, with high turf values and relatively small acreage, and cattle pastures, where the opposite conditions prevailed. As with all nematodes attacking soil insects, the formulations and application methods used needed to prevent dehydration of the nematodes being applied by placing them in the soil at a depth where the target pest could be found by foraging nematodes. Other important factors affecting the acceptability of these nematodes were the need to prevent damage to golf course turf by the application machinery and to keep costs very low (for cattle pastures).

In general, long-term impacts of nematode applications on pest density are not expected, and nematode applications are often akin to using an eco-friendly pesticide, for where the only consequence is short-term pest suppression. However, in a few species of nematodes that are more specific to a particular target pest and more persistent, there can be long-term persistence and suppression of the pest. In these cases, the nematode acts like a classical biocontrol agent. *Steinernema scapterisci* turned out to be one such species, which not only persisted from year to year, but spread long distances through flight of infected (but still functional) mole crickets in the early stages of infection. Consequently, as mole crickets were examined in various places after initial releases, new places were found where the local invasive mole crickets were infected by *S. scapterisci*. For example, in Polk County, Florida, nematologist L. W. Duncan (working from the Citrus Research and Education Center at Lake Alfred) developed a genetic probe for *S. scapterisci* and used it to detect the nematode, which was confirmed to be present in many localities where the nematode had apparently never been applied (L. W. Duncan pers. com.)

Evidence was also obtained that showed *S. scapterisci* could persist for many years at sites where it had once been applied, showing it acted as a classical biocontrol agent. At the request of a prominent Florida cattleman, the South American nematode's persistence was assessed at four of a set of six pastures seven years after the nematode's application in 1989–1990. Pitfall traps were installed at the sites to catch mole crickets, and nematode-infected mole crickets were caught at all four sites (Frank et al., 1999). Similarly, in 2001, a Gainesville golf course, where the nematode had been released 12–13 years earlier, was examined, and the nematode was found to have persisted and to be infecting 10–15% of mole crickets. This not only demonstrated the persistence of the nematodes but also showed that they were highly tolerant to chemical pesticide applications, such as are commonly made on golf courses (Barbara and Buss, 2004).

The ability of this nematode to both persist and spread made it potentially useful to ranchers to control mole crickets in cattle pastures. However, even a single application was too expensive for full treatment of large pastures. This limitation led researchers to test the efficacy of applying the nematode in strips across a pasture, with the expectation that the nematodes would eventually spread on their own after a successful application. The degree of pest control provided by this approach was tested in a 25-acre (10-ha) Bahiagrass pasture. Within three years of the application, pitfall trap catches of mole crickets (*Neoscapteriscus* spp. combined) were reduced by 79.2%, and the Bahiagrass cover increased from 33% to 96% in the same period. Such strip applications reduced the cost of the initial nematode application by 88% (eight times cheaper), but also increased the time required for the nematode to reduce the mole cricket density throughout the pasture (Adjei et al., 2006).

Treatment of any given location even once, however, still required some company to produce and market the nematode. Over time, several different companies were involved, starting with Biosys in California, which marketed the nematode as Vector MC™. This production unfortunately violated the University of Florida's patent, and no agreement on licensed use could be reached by Biosys. Later, a British company called Micro-Bio was able to obtain a license for use from the University of Florida. That company was acquired by Becker Underwood, an American Company, that was willing to send technicians/salesmen to attend meetings with ranchers to explain the product's use. In 2009, J. H. Frank obtained a grant to pay for construction of two application machines that would apply the nematodes correctly to the soil subsurface (**Fig. 5**). These machines are currently available for loan to Florida ranchers who wish to apply *S. scapterisci*. In the long term, such applications on pastures are likely to be unnecessary as the distribution of the nematode expands naturally to be more complete.

Figure 5. Tractor-pulled device for applying nematodes beneath the soil surface. (Lyle Buss, University of Florida)

Ormia depleta

Larvae of this South American fly develop as parasitoids inside mole cricket nymphs and adults. The word 'parasitoid' indicates that it kills its mole cricket host. This is the only known tachinid parasitoid of mole crickets. In eastern South America, it exists as far south as Porto Alegre (30°S) in the Brazilian state of Rio Grande do Sul.

The fly (**Fig. 6**) is known to attack only *Neoscapteriscus* mole crickets, and it finds them at night by orienting to their songs. *Ormia depleta* attacks only two species in the United States (tawny and southern mole crickets), and perhaps some other *Neoscapteriscus* species in South America. Only male mole crickets sing, so they are the stage the fly attacks most often, but females and large nymphs may be attacked if they are close to singing males. Also, both sexes of short-winged mole crickets can be attacked if they are close to singing males of either of the other two host species, but otherwise the fly cannot find them. Species of *Ormia* that are native to the southern United States do not attack *Neoscapteriscus* mole crickets because they are attracted only to the songs of *Gryllus* or *Neoconocephalus* crickets, not those of *Neoscapteriscus* crickets. Therefore, *O. depleta* is safe to non-target organisms in the United States. The adult flies neither bite nor sting people, and because they are only active at night when mole crickets sing, they are unlikely to be seen by people (Walker et al., 1996).

Figure 6. Adult female *Ormia depleta* fly. (Paul Choate, University of Florida)

Adult females of *O. depleta* were first encountered by mole cricket researchers when *Ormia* females were trapped in South America using recordings of mole cricket songs as bait (Fowler and Kochalka, 1985). These flies deposit living larvae (not eggs) on and near singing mole crickets. In quarantine in Florida, work with the native fly *Ormia ochracea* gave clues as to how to get *O. depleta* to reproduce in the laboratory. A rearing method was developed in which larvae were dissected from female flies and placed behind the pronotum of a mole cricket, from where they burrowed into the mole cricket to develop (Wineriter and Walker, 1990).

Using pupae of *O. depleta* reared in the laboratory, we started making field releases of this fly in 1988 at sites near Gainesville and Bradenton. Pupae used in releases were buried approximately ¼ inch (5 mm) in clean, moist sand in a plastic crisper box, which was placed in a cage atop a wooden post embedded in the ground. The placement on a post was done to protect the pupae from disturbance by larger animals. The cage around the plastic crisper box was built of hardware cloth (wire) with a mesh small enough to exclude birds that might eat the fly pupae but that let the adult flies leave. The top of the cage was a piece of plywood with black polyethylene suspended to shade the contents and protect fly pupae from rain. The sand in the release boxes was moistened daily by a spray bottle. Following the release, the sand in the box was sifted to find dead pupae or empty puparia that would indicate successful adult emergence. Based on that information, we estimated more than 90% of the pupae produced adults.

After the initial 1988 trial to develop an effective release method, we started a large program of releases in 1990–1991. Releases in this larger effort were made at 28 golf courses and one sod farm. For these releases more than 10,000 *O. depleta* were reared in mole crickets in the laboratory to supply pupae for releases. At each release site, 200 fly pupae were placed in release cages as described above. The release sites ranged from Ft. Walton Beach in the northwest (near Pensacola) to Naples in southwest Florida (Frank et al., 1996).

In 1992, we began efforts to detect wild fly populations to determine the distribution of *O. depleta* as a measure of the success of the releases. Flies were recovered by attracting them to sound emitters that mimicked mole cricket songs. The emitters were inside heavy plastic bags, and the top of each bag was smeared with "Tack-Trap" (a sticky material used to band fruit trees) to trap the flies arriving to the song source. The 11 sound emitters were positioned along rural roads at approximately 5-mi (8-km) intervals and set to begin operating at sundown. An additional hour was allowed to pass before re-checking the line in reverse. This was done on various dates in June–July 1992, November–December 1992, and November–

December 1994. By the time this survey was finished, the fly had been recovered in 36 Florida counties, all south of approximately 30°N latitude (just south of Jacksonville). Flies did not appear to establish further north, although a few observations of flies were reported there. The maximum number of flies caught in the 'Tack-Trap' was 125, packed 'shoulder to shoulder', at a location in rural Martin County (Frank et al., 1996). That so many flies could have been captured in such a brief time suggests a large population. Efforts to determine what food sources were used by adult flies (like nectar) were unsuccessful. (In the laboratory, we fed them on artificial 'hummingbird' nectar). Walking around at night to try to observe flies feeding on plant nectar achieved one thing: bumping into trees.

Other Potential Biocontrol Agents Tested

Two other agents were investigated in this program, which ultimately were either not successful or unsuitable. One of these agents was *Pheropsophus aequinoctialis*, a predatory ground beetle (Carabidae) in a group known as bombardier beetles. *Pheropsophus aequinoctialis* is widespread in South and Central America, and T. L. Erwin suggested to a member of the mole cricket program that larvae of this beetle might be predators of mole cricket eggs. *Pheropsophus aequinoctialis* was imported from Bolivia and later Brazil into a Florida quarantine facility for study. We learned that larvae of *P. aequinoctialis* can feed on eggs of all four mole cricket species in Florida, but this group included the native mole cricket *N. hexadactyla* (Frank et al., 2009b). Consequently, this beetle was rejected for possible release.

Another agent that was considered was the fungal pathogen *Beauveria bassiana*. In small containers, applications of *B. bassiana* to the surface of mole crickets killed them, and the idea we investigated was to create a bait that could be mixed with fungal spores, which would attract mole crickets. Unfortunately, there appeared to be a trade-off: using a large amount of bait and little fungus attracted mole crickets but did not kill them; using little bait but a large amount of fungus caused the fungus to repel the mole crickets. We needed a cheap but super-attractive bait. As we never found one, this approach was abandoned without being used.

HOW WELL DID IT WORK?

The mole cricket research program ended in 2004 because its objectives had been achieved. In 2004, of the original seven mole cricket trapping stations, five had been terminated due to operators retiring or relocating. The penultimate station was almost abandoned in 2002, when the university farm on which it operated was sold to the county government for development; but mole cricket researchers petitioned the county government to allow its continued operation for two more years until the county government had finished its plans for development. Data from these stations were compiled by Frank and Walker (2006) to document the decline of both mole cricket species caught in traps, which was first noticed in 1990. The data showed that by the end of the program, mole cricket densities had declined by 95% compared to first nine years of trapping (1979–1988), which corresponded to a period before the released natural enemies began showing up at the trapping stations. During the first nine years of this trapping effort, the trend in annual catches was static (**Fig. 7**), showing that trapping of mole crickets itself had no effect on the local population density. Starting in1990, trap catch began to decline, and it continued to drop until about 2000 when it levelled off. Mole cricket decline was clearly due to the natural enemies released (*L. bicolor*, *O. depleta*, and *S. scapterisci*) but the relative contributions of each agent to this control are unknown and may have varied from place to place. (Note that the histogram in **Fig. 7** shows data per 'generational year,' from August in one year through July the next year, to reflect mole cricket reproduction. We considered the average catch during years 1979–1988 to be the 'baseline' because none of the biological control agents showed up at our trapping stations until 1988).

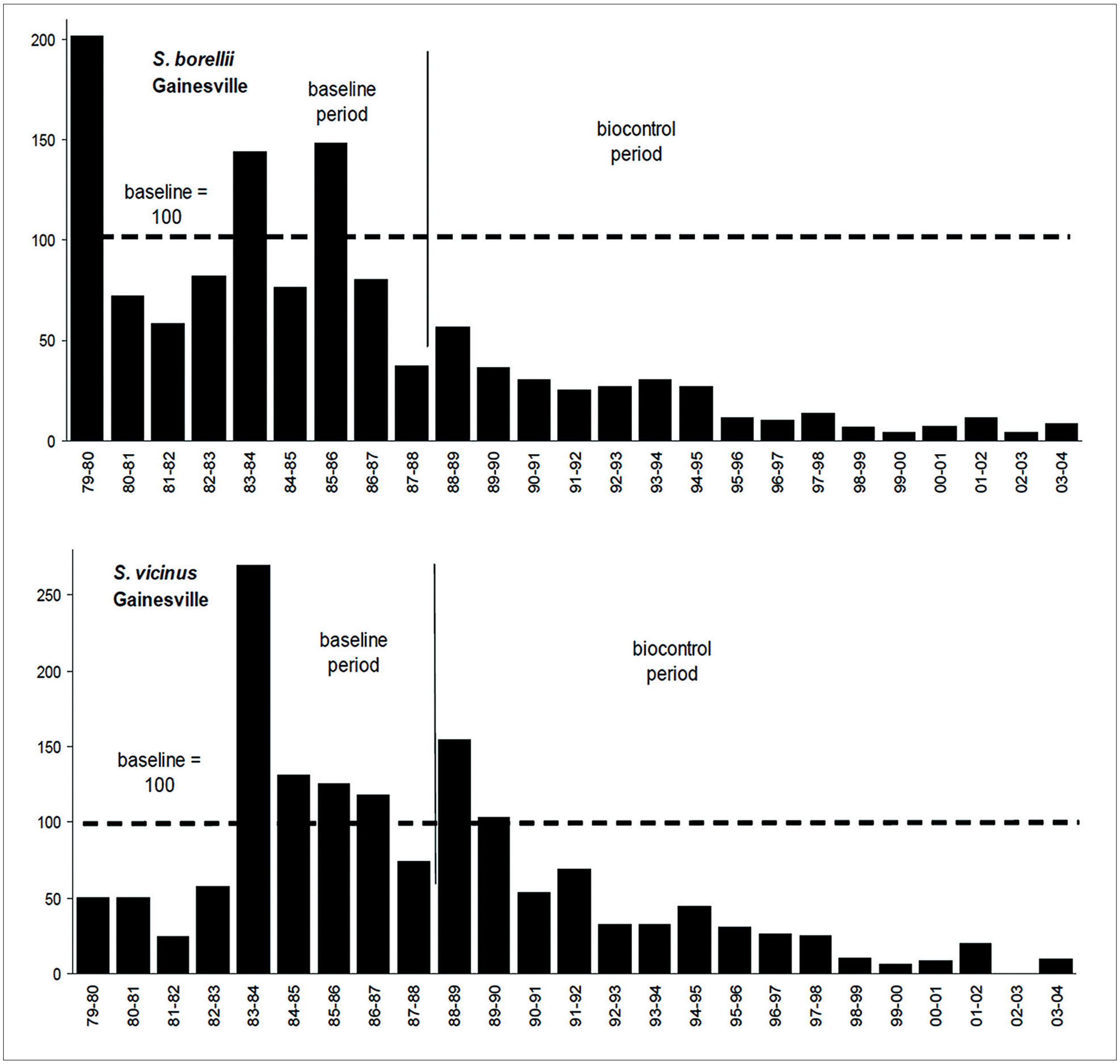

Figure 7. Histograms showing numbers of southern mole cricket, *Neoscapteriscus* (=*Scapteriscus*) *borellii*, and tawny mole cricket, *Neoscapteriscus* (=*Scapteriscus*) *vicinus*, captured (averaged by species and combined over two trapping stations) from 1978–79 to 2004–05. Biocontrol agents were present at the stations by 1990, and they caused the subsequent decline in mole crickets captured. (from Frank and Walker, 2006, reprinted with permission from Oxford University Press)

As a post-datum, we can point out that about 2011, Becker Underwood stopped producing *S. scapterisci* because sales were too low to make an adequate profit to justify continued production. This is likely a case where the very success of the program doomed the future sale of a product that depended for its existence on a continuing pest problem. Regardless, the ability of this nematode to persist and to spread means it is expected to remain a vital part of mole cricket suppression in Florida indefinitely. Furthermore, the nematode is not immobile, as it is spread by newly infected mole crickets, allowing it to spread to new locations over time. Unlike other insect-killing nematodes, this species' populations can survive for many years, if not indefinitely, in a local area if some mole crickets remain. In addition to pastures, owners of organic farms, lawns, and golf courses are expected to benefit from this nematode.

The mole cricket biocontrol program was started at the request of ranchers. A study of the economics of the benefit to Florida ranchers (Mhina et al., 2016) suggested that mole cricket biological control reduced losses from mole crickets in pastures to unimportant levels. The long-term economic benefit of the project had a benefit: cost ratio of 52:1, and its overall annual benefits in terms of avoided pest control and renovation of pastures alone were $13.6 million.

The public benefited from the mole cricket biocontrol program through the reduction of the nuisance that high densities of mole crickets used to cause during outdoor events, such as during nighttime sporting events (in which mole crickets were attracted to outdoor lighting and then landed on people). Mole crickets also no longer swarm around lights in the parking lots of supermarkets and such businesses as convenience stores. Benefits to golf courses were less significant because mole crickets were only one pest among several (although mole crickets for decades have been the most important pests on golf courses in Florida). Only with the decline in numbers of mole crickets did the lesser problem of white grubs surface. Because other pests (such as white grubs) still needed to be treated with broad-spectrum pesticides, suppressing mole crickets with biological control by itself did not reduce pesticide use on golf courses.

The biological control agents released against *Neoscapteriscus* mole crickets in Florida are highly specific to the invasive mole crickets they attack. They do not attack other kinds of mole crickets, such as species of *Gryllotalpa* or *Neocurtilla*, which belong to a different mole cricket subfamily (Gryllotalpinae). Consequently, no effects occurred or are expected in the future on any of these other cricket groups, due to the high specificity of the agents used. Thus, non-target species are protected from harm.

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REFERENCES

Adjei, M. B., G. C. Smart, Jr, J. H. Frank, and N. C. Leppla. 2006. Control of pest mole crickets (Orthoptera: Gryllotalpidae) on pasture with the nematode *Steinernema scapterisci* (Rhabditida: Steinernematidae). *Florida Entomologist* 89: 532–535.

Barbara, K. A. and E. A. Buss. 2004. Survival and infectivity of *Steinernema scapterisci* (Nematoda: Steinernematidae) after contact with soil drench solutions. *Florida Entomologist* 87: 300–305.

Castner, J. L. 1988. Biology of the mole cricket parasitoid *Larra bicolor* (Hymenoptera: Sphecidae) pp. 423–432. *In:* Gupta, V. K. (ed.) *Advances in Parasitic Hymenoptera Research, 1988*. Brill Publications, Leiden, Netherlands.

Fowler, H. G. and J. N. Kochalka. 1985. New record of *Euphasiopteryx depleta* (Diptera: Tachinidae) from Paraguay: attraction to broadcast calls of *Scapteriscus acletus* (Orthoptera: Gryllotalpidae). *Florida Entomologist* 68: 225–226.

Frank, J. H. and A. Sourakov. 2002. *Larra* wasps, mole cricket hunters, *Larra analis* Fabricius and *Larra bicolor* Fabricius. (Insecta: Hymenoptera: Crabronidae). Featured Creatures (University of Florida) EENY-268. https://entnemdept.ufl.edu/creatures/beneficial/Larra_wasps.htm (revised February 2017).

Frank, J. H. and T. J. Walker. 2006. Permanent control of pest mole crickets (Orthoptera: Gryllotalpidae: *Scapteriscus*) in Florida pastures. *American Entomologist* 52: 138–143.

Frank, J. H., J. P. Parkman and F. D. Bennett. 1995. *Larra bicolor* (Hymenoptera: Sphecidae), a biological control agent of *Scapteriscus* mole crickets (Orthoptera: Gryllotalpidae), established in northern Florida. *Florida Entomologist* 78: 619–623.

Frank, J. H., T. J. Walker and J.P. Parkman. 1996. The introduction, establishment and spread of *Ormia depleta* in Florida. *Biological Control* 6: 368–377.

Frank, J. H., C. Grissom, C. Williams, E. Jennings, C. Lippi, and R. Zerba. 1999. A beneficial nematode is killing pest mole crickets in some Florida pastures and is spreading. *Florida Cattleman* 63(7): 31–32.

Frank, J. H., N. C. Leppla, R. K. Sprenkel, A. C. Blount, and R. F. Mizell III. 2009a. *Larra bicolor* Fabricius (Hymenoptera: Crabronidae): its distribution throughout Florida. *Insecta Mundi* 0063: 1–5.

Frank, J. H., T. L. Erwin, and R. C. Hemenway. 2009b. Economically beneficial ground beetles. The specialized predators *Pheropsophus aequinoctialis* (L.) and *Stenaptinus jessoensis* (Morawitz): Their laboratory behavior and descriptions of immature stages (Coleoptera, Carabidae, Brachininae). *Zookeys* 14: 1–36.

Hudson, W. G. and K. B. Nguyen. 1989. Effects of soil moisture, exposure time, nematode age, and nematode density on infection of *Scapteriscus vicinus* and *S. acletus* (Orthoptera: Gryllotalpidae) by a Uruguayan *Neoaplectana* sp. (Rhabditida: Steinernematidae). *Environmental Entomology* 18: 719–722.

Kepner, R. K. and S. J. Yu. 1987. Development of a toxic bait for control of mole crickets (Orthoptera: Gryllotalpidae). *Journal of Economic Entomology* 80: 659–665.

Lengyel, K. In: Lengyel, K., E. Lang, A. Fodor, E. Szállás, P. Schumann and E. Stackebrandt. 2005. Description of four novel species of *Xenorhabdus*, family Enterobacteriaceae: *Xenorhabdus budapestensis* sp. nov., *Xenorhabdus ehlersii* sp. nov., *Xenorhabdus innexi* sp. nov. and *Xenorhabdus szentirmaii* sp. nov. *Systematic and Applied Microbiology* 28: 115–122.

Mhina, J. G., N. C. Leppla, M. H. Thomas, and D. Solis. 2016. Cost effectiveness of biological control of invasive mole crickets in Florida pastures. *Biological Control* 100: 108–115.

Nguyen K.B, and G. C. Smart. 1990. *Steinernema scapterisci* n. sp. (Rhabditida: Steinernematidae). *Journal of Nematology* 22: 87–199.

Nguyen, K.B. and G. C. Smart.1992. *Steinernema neocurtillis* n.sp. (Rhabditida: Steinernematidae) and a key to the species of the genus *Steinernema*. *Journal of Nematology* 24: 463–467.

Parkman, J. P., J. H. Frank, K. B. Nguyen, and G. C. Smart.1993. Dispersal of *Steinernema scapterisci* (Rhabditida: Steinernematidae) after inoculative applications for mole cricket (Orthoptera, Gryllotalpidae) control in pastures. *Biological Control* 3: 226–232.

Portman, S. L., J. H. Frank, R. McSorley, and N. C. Leppla. 2009. Fecundity of *Larra bicolor* (Hymenoptera: Crabronidae) and its implications in parasitoid: host interaction with mole crickets (Orthoptera: Gryllotalpidae: *Neoscapteriscus*). *Florida Entomologist* 92: 58–63

Portman, S. L., J. H. Frank, R. McSorley, and N. C. Leppla. 2010. Nectar-seeking and host-seeking by *Larra bicolor* (Hymenoptera: Crabronidae), a parasitoid of *Neoscapteriscus* mole crickets (Orthoptera: Gryllotalpidae). *Environmental Entomology* 39: 939–943.

Sellers, B. A., L. D. Butler, and J. McWhorter. 2016. Biology and management of whitehead broom in pastures. UF/IFAS Extension SS-AGR-406. https://edis.ifas.ufl.edu/publication/AG409 (revised December 2019)

Walker, T. J. 1982 Sound traps for sampling mole cricket flights (Orthoptera: Gryllotalpidae: *Scapteriscus*). *Florida Entomologist* 65: 105–110.

Walker, T. J. and D. A. Nickle. 1981. Introduction and spread of pest mole crickets: *Scapteriscus vicinus* and *S. acletus* reexamined. *Annals of the Entomological Society of America* 74: 158–163.

Walker, T. J., J. P. Parkman, J. H. Frank, and D. J. Schuster. 1996. Seasonality of *Ormia depleta* and limits to its spread. *Biological Control* 6: 378–383.

Wineriter, S. A. and T. J. Walker. 1990. Rearing phonotactic parasitoid flies (Diptera: Tachinidae, Ormiini, *Ormia* spp.). *Entomophaga* 35: 621–632.