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RESEARCH ARTICLE

Pesticide-free management of invasive ants impacting ground-nesting wildlife populations

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Abstract

Nonnative, invasive ants, and especially the red imported fire ant, *Solenopsis invicta*, are a widespread threat to ground-nesting wildlife. In this paper I describe a method of controlling fire ants using hot water. The hot water approach was applied to reduce fire ant impacts on sea turtles and ground-nesting songbirds and to demonstrate its utility in protection of different ground-nesting species in different habitats. Fire ant controls using hot water provided 90% or greater control, significantly improving survival of both turtle and bird hatchlings, without the use of pesticides. The success of the method and the availability of necessary equipment shows that hot water control of fire ant populations should be considered as a tool for wildlife affected by fire ants and is useful for a wide variety of scenarios where fire ant controls are desirable or necessary. The method does require that 1) wildlife nest locations are known and that 2) nearby fire ant colonies can be found and treated with hot water. The method can be used as a complement to broadcast or bait-station baiting strategies or as a stand-alone method for managing fire ants.

KEYWORDS

Ammodramus savannarum floridanus, *Caretta caretta*, fire ants, Florida grasshopper sparrow, hot water, nest predation, nonnative species, pest control, sea turtles, *Solenopsis invicta*

Nest predation affects reproductive success for ground-nesting vertebrates (Newton 1998, Banks et al. 2008, Pauliny et al. 2008, Mainwaring et al. 2017). Nonnative, invasive ants are important predators of ground-dwelling and ground-nesting vertebrates including birds, herpetofauna, and small mammals (Stake and Cimprich 2003, Allen et al. 2004, Smith et al. 2007, Todd et al. 2008, DeFisher and Bonter 2013). Ants are particularly effective predators of eggs and small, immobile juveniles in nests on or in the ground because they will forage up to 24 hours per day above- or below-ground, can rapidly recruit to food resources, and can also envenomate (sting) and cause rapid mortality of small-bodied prey.

Two of the most important nonnative, invasive ants affecting wildlife populations are the red imported fire ant (RIFA; *Solenopsis invicta* Buren), and the tropical fire ant (TFA; *Solenopsis geminata* [Fabricius]; Allen et al. 2004, Wetterer et al. 2007, Plentovich et al. 2009). Invasions of both species of fire ants have demonstrated negative impacts on vertebrate wildlife (especially ground nesting birds and herpetofauna) and may also affect arthropod communities (Holway et al. 2002, King 2020*a*, Epperson et al. 2021). Wildlife impacts may be especially common on islands (Wetterer 2011, Wauters et al. 2018). Unlike many nonvenomous invasive ants, fire ant impacts on wildlife may be realized at very low densities as even a single colony can negatively impact nearby eggs and juveniles (Allen et al. 2017). Fire ants have been spread to every continent except Antarctica and a number of islands (Tschinkel 2006, Ascunce et al. 2011, Wetterer 2011, Wylie et al. 2019) and thus are now a potential threat to ground-nesting vertebrate wildlife in a wide variety of ecosystems. A long-established concern in North, Central, and South America, increasing prevalence of fire ants in the Asia-Pacific region (Gruber et al. 2017, 2021; Wylie et al. 2019) establishes RIFA and TFA as a global concern for wildlife.

Currently, insecticide-based control methods are the primary tool available for managing problematic invasive ant populations (Hoffmann et al. 2011), including fire ants (Drees et al. 2013). Eradication of fire ants (and most other invasive ants) throughout their invasive range is not currently feasible anywhere populations have expanded beyond approximately a square kilometer or more (Drees and Gold 2003, Tschinkel 2006, Hoffmann et al. 2011, Wylie et al. 2019). As a consequence, reducing fire ant numbers in small areas requires ongoing maintenance as areas cleared of fire ants are rapidly recolonized, often at densities higher than pretreatment, if management ends (Stimac and Alves 1994, Morehart et al. 2022). Insecticides are the central part of the existing integrated pest management (IPM) plans for controlling fire ants (Drees and Gold 2003, Drees et al. 2013) and most other invasive ants, largely because existing nonchemical and biological control methods have yet to match the levels of control that can be achieved with chemical control (Morrison and Porter 2005, Drees et al. 2013). There are no widely adopted, established IPM strategies for managing fire ants and other invasive ants impacting wildlife and other scenarios where pesticide inputs are neither desirable nor possible (Oi and Drees 2009, Drees et al. 2013).

There are a small number of noninsecticidal approaches to eliminating individual mounds that have shown limited effectiveness for local control efforts. These approaches include physical removals (i.e. digging up) of colonies, naturally occurring (nonsynthetic) compound application, and hot water application (Tschinkel and Howard 1980, Drees and Gold 2003, Drees et al. 2013, Chen and Oi 2020). Of these, only hot water has shown the potential to provide comparable levels of local control as insecticides (King and Tschinkel 2006, Middleton et al. 2023). Hot water drenching (pouring large volumes of very hot water directly on fire ant mounds) was first demonstrated as an available technique for eliminating small numbers of mounds in situations where insecticide use is not desirable (Tschinkel and Howard 1980). Hot water drenching has subsequently been used to protect endangered cave fauna by eliminating fire ant colonies at the mouth of caves (Elliot 1993). Hot water drenching has also been tested as a possible control method in urban environments (Fernandes et al. 2020), and used in ecological experiments to manipulate fire ant densities (King and Tschinkel 2006, 2008, 2013; Tschinkel and King 2007). In all of the above scenarios, hot water drenching provided comparable control of fire ants to reported control rates with insecticides (baits and/or sprays). More recently, the low-pressure, hot water injection method has been tested as a method for managing fire ants in citrus agroecosystems (Middleton et al. 2023). In sum, previous research suggests that the use of hot water, and especially the use of low-pressure hot water injection, is a method that can be used as a centerpiece for developing nontoxic IPM strategies for fire ants and other invasive ants or as a complement to toxic baiting strategies if both are management options.

Here I describe the use of low-pressure hot water injection into fire ant mounds to successfully control fire ant populations threatening ground-nesting wildlife. The focus is on RIFA, but the methods also apply to managing TFA as their nest structure and ecology are similar (author, personal observation; Tschinkel 2006). I describe application of the method in defense of endangered beach-nesting sea turtles and critically endangered Florida dry prairie songbirds (Florida grasshopper sparrows) as a proof-of-concept test for use of low-pressure hot water injection as an added component to invasive ant, and especially fire ant, management programs.

STUDY AREA

The work described here was conducted over the period spanning spring (April) to late summer (September) in the years of 2015–2018 in 2 locations, one in mixed pasture and dry prairie habitats of central Florida, and the other in coastal dune and beach habitats of the central west coast of Florida (Figure 1). These studies were separated in time and space but the same general approach was applied to managing fire ant colonies in proximity to vertebrate nests on or in the ground. Both are included here to demonstrate the general utility of the approach and methods to managing fire ants in very different habitats and for very different ground-nesting vertebrate wildlife species.

Sea turtles

RIFA controls were conducted by the author from April–September 2015 (the sea turtle nesting season in Florida) at Fort De Soto Park, Pinellas County, on the west coast of Florida, USA. Fort De Soto Park is a series of 5 keys (small islands) connected by paved roadways. The park is 460 ha in total size and includes ~5 km of beaches and a variety of natural areas such as coastal dunes, coastal hammocks, and mangrove communities. All of the natural areas are in close proximity to a variety of human-modified environments including buildings, roads, parking lots, piers, nourished beaches, and walking trails. On average, over 2.7 million people visited the park each year during

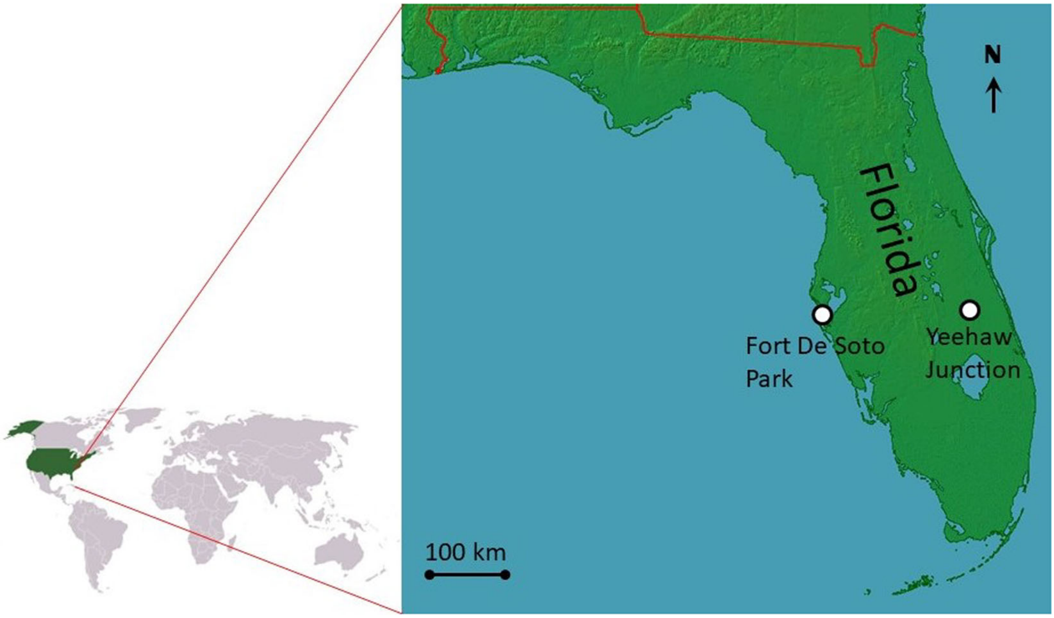

FIGURE 1 Florida, USA, with the study site locations of the fire ant controls around Florida grasshopper sparrow nests (Yeehaw Junction) and sea turtle nests (Fort De Soto Park).

the period of work (Pinellas County, Florida, Parks and Preserves 2016), and thus human recreational activities were widespread across the park landscape.

Prior to the study, there had been an average of 83 loggerhead sea turtle (*Caretta caretta* Linnaeus) nests laid on Fort De Soto Park beaches per year (Florida Fish and Wildlife Conservation Commission [FWC] 2015). Sea turtles nest above high tide lines along beaches, often in close proximity to dune ecosystems found on the inland margin of beaches. Loggerhead sea turtles are listed as a threatened species in the U.S. and the work described here was conducted under the guidance and permission of the Florida Fish and Wildlife Conservation Commission (FWC) and the marine turtle permit holder (Fort De Soto Park) staff responsible for monitoring sea turtle nests at the park.

As part of their statewide monitoring of sea turtle nesting activities on beaches, the FWC and the Fish and Wildlife Research Institute reported that during the period 2012–2014, an average of 62 survey beaches in Florida reported problems with ants, primarily fire ants (FWC Statewide Nesting Beach Survey database, https://myfwc.com/research/wildlife/sea-turtles/nesting/monitoring/, accessed November 2016). The reported area represented approximately 30% of the 212 beaches (covering approximately 1,300 km of coastline) monitored in the state of Florida. On average, 20 of the site managers of affected sites reported using a broadcast insecticidal bait, such as Amdro™ (Central Garden & Pet Co., Walnut Creek, CA, USA; a hydramethylnon-based hydrazone insecticide available as a bait that ants pick up), to attempt to reduce or control fire ants. As of November 2013, there was an increasing incidence of problems with fire ants at Fort De Soto Park when the park submitted annual data on nesting turtles. In 2013, 26% (17 of 66) of nests laid in Fort De Soto were affected by RIFA. Similar impacts were reported for 2014. In cases of RIFA predation, affected nests had all or nearly all hatchlings killed by RIFA. Broadcast bait controls had been used for years prior to and including the 2013–2014 period and were not effective in sufficiently reducing RIFA predation on sea turtle nests at Fort De Soto Park (as reported by park staff). Given the unique issues of problematic fire ant populations, human recreation, and wildlife (sea turtle nesting) concerns for this site, FWC sought guidance from the author to test a more effective fire ant management plan.

Florida grasshopper sparrows

Fire ant controls were conducted from April–July (the Florida grasshopper sparrow [*Ammodramus savannarum floridanus*; hereafter FGSP] nesting period in Florida) in 2017–2018. The Florida grasshopper is a critically endangered subspecies of the more widespread grasshopper sparrow (*Ammodramus savannarum*) whose population is endemic to the south-central dry prairie region of Florida (Noss et al. 2008, Blackford et al. 2019). Populations at all remaining breeding sites in the remaining fragments of treeless dry prairie habitats of south central Florida are declining rapidly (Ragheb et al. 2019*b*). The probable cause of declines is likely a synergistic interaction of changing fire regimes and land use, predation pressure, and inbreeding effects (Endangered and Threatened Wildlife and Plants; Determination of Endangered Status for the Florida Grasshopper Sparrow [1986, 50 CFR § 17]). In 2014, an adaptive management plan was enacted to attempt maintenance and rehabilitation of wild populations (Florida Grasshopper Sparrow Working Group, unpublished report). The effort depends upon maintaining existing wild breeding populations, establishing a captive breeding population, and reintroducing birds back into the wild to increase the size of small existing wild populations. Mitigation of fire ants in support of the FGSP protection plan took place on a private cattle ranch, located approximately 40 km from Three Lakes Wildlife Management Area in Osceola County, Florida, USA, and at 2 private wildlife breeding facilities. The wildlife breeding facilities were where captive breeding of FGSP was being conducted and area-wide fire ant controls were desired at these sites as the birds were kept in outdoor enclosures and fire ants were present throughout the areas where the birds were being maintained. The captive breeding sites are located near the towns of Loxahatchee in south Florida and Yulee in north Florida.

As FGSP are ground-nesting birds, mitigation of nest predation was recognized as a crucial management strategy as part of managing remaining wild populations (Ragheb et al. 2019*a*) as well as during captive breeding efforts. Nest predation accounts for nearly 90% of nest failures and fencing around FGSP nests has been shown to be very effective at excluding vertebrate nest predators (e.g., *Pantherofus guttatus*, *Spilogale putorius*, *Procyon lotor*; Ragheb et al. 2019*a*). However, RIFA remained a persistent predation threat after fencing (Ragheb et al. 2019*a*), especially in the remaining site where FGSP breeding populations are found (author, personal observation). Florida grasshopper sparrow populations persist in a mixture of improved and semi-improved cattle pasture and dry prairie habitats. These habitats in central Florida consistently support moderate to high densities of RIFA (Steele et al. 2020). Chemical controls of ants with toxic baits cannot be safely used in proximity to the remaining breeding population. The common prey items of these insectivorous songbirds (e.g., crickets and grasshoppers and other arthropods) may be affected by broadcast ant baits (Tschinkel 2006; Plentovich et al. 2010, 2011; Korosy 2013; Sakamoto et al. 2019). Additionally, FGSP populations persist in areas of frequent cattle grazing, and most broadcast baits are not registered for use in pastures.

In 2016, U.S. Fish and Wildlife Service (FWS) determined that once nests were fenced against vertebrate predators, RIFA remained an important nest predator, primarily attacking newly hatched nestlings. Further mitigation efforts were needed to reduce RIFA impacts on wild populations and to protect captive breeding populations, and thus the author was contacted to attempt nontoxic controls of fire ants in the vicinity of nesting FGSP. In 2016, a small pilot study was conducted, where 4 FGSP nests were treated for fire ants. Based on the success of those nests (and lack of fire ant predation), a larger control effort was conducted in 2017 and 2018.

METHODS

In 2012, I designed the original prototype of a trailer-based, hot water system to be used for controlling fire ants without the use of insecticides (Figure 2A). The generalized apparatus and method of control has been patented as an environmentally-safe insect control system (King 2020*b*). The general design can be modified, effectively altering the size and weight of the system to improve mobility across a wider variety of urban, suburban, and natural landscapes and to reduce potential vehicle-caused impacts due to weight, depending upon the application scenario (Figure 2A–C). Briefly, the hot water apparatus has a water tank, a motor, an electrical system, a pump, hoses, a water heating system, and an injection wand for delivering water belowground into the colony structure. The pump is run by a chain or belt drive powered by the motor. The water flows from the reservoir tank through the pump, flowing then to the heating unit. The heating unit is powered by a heating system (a burner) wherein a water-filled coil is exposed to high temperatures in a chamber heated by igniting fuel (typically diesel or propane that is stored on the trailer and pumped to the burner unit) and that transfers heat to the water flowing through the coils in the chamber. The temperature of the water is under thermostatic control by the operator. Once heated the water flows out of the heater unit to an insulated hose (~30 m in length) with a wand attached to allow application of the water away from the trailer. The heated water is ~87–95°C at the wand as it is delivered belowground into the fire ant colony under low pressure at a rate of ~19 L (or less) per minute (Figure 3). For this study, water temperature was maintained at ~90°C from the tip of the wand for all treatments.

Sea turtles

Sea turtles nest above the high tide line in or on the margin of the dune ecosystem along Florida beaches. In the dune ecosystems, RIFA commonly nest at the base of a variety of plants that are common in these ecosystems (author, personal observation). These include saltwort (*Batis maritima*), sea oat (*Unioloa paniculata*), beach morning glory (*Ipomoea pes-caprae*), common sandbur (*Cenchrus spinifex*), and sea purslane (*Sesuvium portulacastrum*). I visually searched to find RIFA colonies within a ~10-m radius in all directions around sea turtle nests. This is the general spatial footprint and RIFA management approach using hot water controls for wildlife protection scenarios

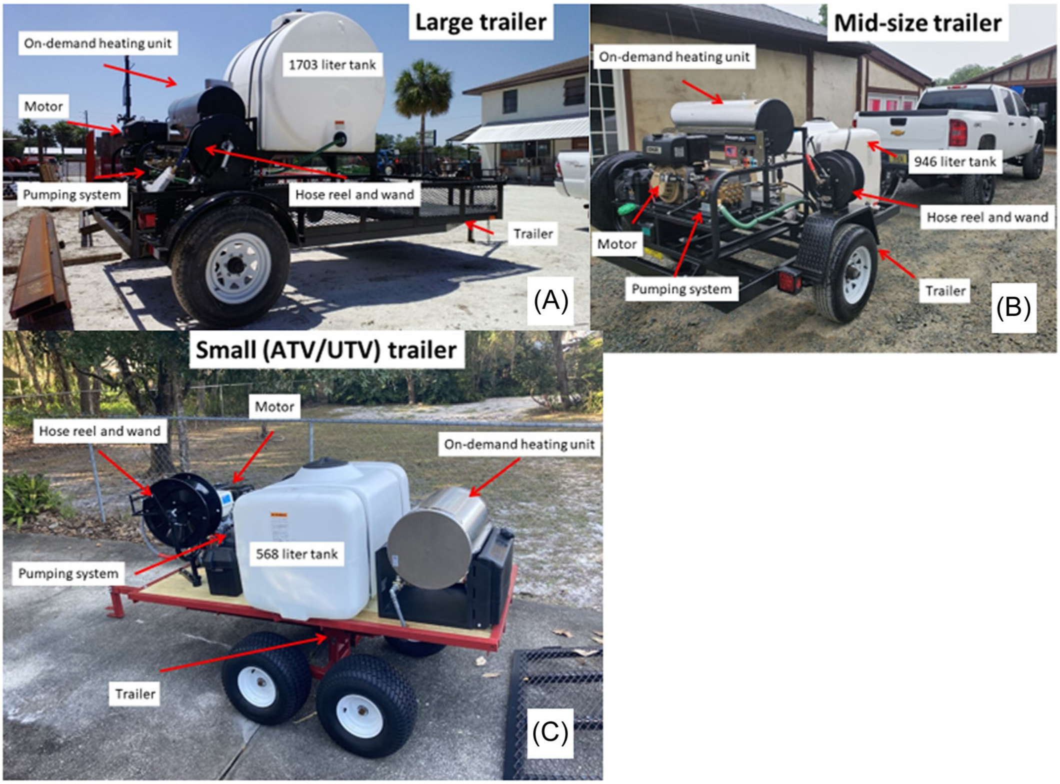

FIGURE 2 A. Large, trailer-based, hot water-generating device for controlling invasive ants. Towed by on- or off-road vehicles and designed for on- and off-road use. B. Mid-sized, trailer-based, hot water generating device for controlling invasive ants. Towed by on- or off-road vehicles, and designed for on- and off-road use. C. Small, trailer-based, hot water generating device for controlling invasive ants. Towed by all terrain or utility vehicles and designed for off-road use only.

as it permits rapid discovery and control of RIFA colonies within likely foraging range of RIFA nearby the wildlife species' nests.

Sea turtle nests, flagged and monitored by park staff, were used as the center of the 10-m search radius. Fire ant colonies were flagged for control when discovered. Fire ants can penetrate sea turtle eggs (as opposed to avian eggs; Diffie et al. 2010) but generally appear to have a much greater impact as predators by attacking hatchlings during pipping or once they have emerged from eggs (Allen et al. 2001). Thus, the goal of the control program was to reduce fire ant populations in close proximity to sea turtle nests and to maintain the fire ant-free zone, centered on the sea turtle nest, over the course of the 4 months-long nesting period, so there were few or no RIFA present during the hatching and emergence period.

Fire ant control was thus maintained until just prior to when hatchlings pipped and exited their eggs below ground and made their way to the ocean, which typically occurs within ~24 hours of emerging from their eggs and nest. Beginning in June and continuing through early September, hot water was used to kill any fire ant colonies detected within ~10 m of sea turtle nests. Every nest that was accessible by the hot water trailer (towed by a truck) was treated in 2015 at least once. Over the course of 5 visits (1 workday or 8 hr-long) during the nesting period, each sea turtle nest was checked 3–5 times throughout the nesting period, to assure that colonies did not move into areas where fire ant colonies were previously killed. Checks entailed eliminating any newly founded colonies and making certain that any ant colony fragments were eliminated if the initial hot water treatment did not kill the colony.

FIGURE 3 The hot water method of treating fire ant mounds in Florida, USA. On the right, images of nest casts of the inner spaces of mounds allow visualization of the method. Images and nest casts were made by W. Tschinkel and are used with permission. In the leftmost image, the wand is inserted by the author into a fire ant mound (approximately where the red dot appears on the upper right image of the mound). The stainless-steel nozzle is inserted within the tunnel and chamber structures created by the ants, belowground (visualized on the bottom right image), and hot water (~87–92°C) is injected under low pressure at a rate of ~19 L per minute, slowly filling the mound with hot water from bottom to top. The mound (above the ground surface) is completely washed away, once the belowground chambers have been filled and flooded out.

Florida grasshopper sparrows

The breeding population of sparrows is very small and persists in a semi-natural pasture landscape with dense groundcover including native (e.g., wiregrass *Astrida beyrichiana*) and nonnative grasses, saw palmetto (*Serenoa repens*), runner oak (*Ilex glabra*), and fetterbush (*Lyonia lucida*). This makes nest discovery challenging. As the sparrows are a critically endangered subpopulation, nesting pairs were monitored by FWC staff. Nevertheless, finding bird nests and administering fire ant treatments prior to fledging was sometimes not possible. Thus, this resulted in a situation where some bird nests could be treated for fire ant control and some could not in both 2017 and 2018 (thus there were control and treatment nests for analyses, albeit in an unbalanced design).

Because FGSP nests were located and monitored by FWC staff, eliminating fire ants in a ~10 m radius around FGSP nests was possible if nests were discovered with sufficient time prior to eggs hatching. As with sea turtles, I visually searched to find fire ant colonies within a ~10-m radius in all directions around FGSP nests. Florida grasshopper sparrow nests, placed by females over the course of the nesting season, were used as the center of the search radius. Colonies were flagged for control when discovered. Fire ant colonies were removed with hot water treatment by the author. The nesting period (eggs to fledglings departing the nest) is usually 19–22 days (Vickery 1996) and nesting can occur any time between March and August. Thus, the search protocol for RIFA colonies was the same as performed for sea turtle nests, but the period of controls (colony removals) was much shorter and typically only one round of fire ant colony removals was possible prior to chicks leaving the nest. Fire ants have not been shown to attack FGSP eggs but do attack hatchlings (Ragheb et al. 2019*a*). Fledging occurs 8–9 days after hatching and once fledglings leave the nest and are mobile, they are less vulnerable to fire ant predation.

In the captive breeding facilities, as birds were contained in large enclosures, an areawide control (find and eliminate any colonies detected with hot water) was enacted such that all fire ant colonies within ~20 m of the captive breeding enclosures were killed by the author once each year and opportunistically as needed. This encompassed nearly a hectare of area in the larger, north Florida captive breeding site and roughly 0.4 ha (an acre) in the smaller south Florida captive breeding site. The amount of time required (and the amount of hot water used) to kill fire ant colonies in captive breeding facilities was determined by the amount of time required to completely fill belowground chambers and the aboveground mound of fire ant colonies averaged across all of the colonies in the larger captive breeding site.

The primary variable of interest for both species was the number of surviving hatchlings that made it out of the nest. For sea turtles, the mortality rate (deaths per total number) of hatchlings attributable to fire ant predation was also considered. The cause of FGSP hatchling mortality was not always certain (nor was the cause of mortality for eggs), so mortality was not analyzed for FGSP. Fire ant predation of hatchlings was verified via park personnel observations of sea turtle nests as part of regular monitoring during hatching periods and, when possible, it was verified for FGSP via nest cameras or direct observation by FWC personnel. As these were endangered species, fire ant management approaches and the resulting analytical approach to results differed for each species, as described below, due to differences in timing of nesting, duration of nesting, management concerns specific to the site, and access to nests during critical periods.

For sea turtles, data were assessed as mortality rate of individuals and total hatchling survival across nests in the 2013 versus 2015 season. In 2013, sea turtle nests were not manipulated (dug up by park staff) as they were in 2014, and thus fire ant predation occurred on a number of nests. In 2014, park personnel collected all RIFA impacted nests immediately, and thus almost entirely eliminated fire ant-caused mortality; therefore, those data were not analyzed. Within-year experiments (treatment versus no treatment) comparisons were not possible as the goal for this particular scenario (and the funding agency) was to provide protection for all accessible nests. Thus, treatment versus no treatment comparisons were made between the most recent year prior when park personnel did not intervene in hatching (2013) and the year when hot water was used for fire ant removals (2015) using a before-after control-impact (BACI) analysis approach. Of note, mortality of sea turtles includes death of pipped eggs (shell of the egg broken but hatchling not emerged as it was killed in the egg) plus mortality of hatchlings.

For FGSP, hatchling survival comparisons were made between treated and untreated nests in 2017 and 2018 (years when fire ants were removed across the entire breeding season) in an unbalanced ANOVA analysis. Data for the areawide control in the captive breeding site were not analyzed statistically and results are simply reported as no mortality attributable to RIFA were recorded when management was taking place.

Data were analyzed in a generalized linear mixed model framework (GLIMMIX) in SAS version 9.4. In SAS, PROC GLIMMIX allows for error terms that are not normally distributed and allows for random effects in models. Variables were fit to generalized linear mixed models using normal, Poisson, or negative binomial distribution as best fit the data and checked for overdispersion (Littell et al. 2006). Type III *F*-statistics for fixed effects (survival, mortality) were calculated which Author report here as *F*-statistics and associated *P*-values. I examined the result of multiple comparisons here as *P*-values after Tukey-Kramer adjustment to assess differences.

RESULTS

Fire ants were found nesting throughout the coastal dune ecosystems along the beaches at Fort De Soto Park, although they were not present in the vicinity of every sea turtle nest. In 2013, 66 nests were deposited, 18 nests were attacked by RIFA resulting in the death of 430 hatchlings (Table 1). By comparison, in 2015 4 nests had a total of 36 hatchlings killed by RIFA, across the 68 nests that were monitored and treated if fire ants were detected. In

TABLE 1 Sea turtle hatchling mortality and survival in 2013 versus 2015, Florida, USA.

Year	Turtle nests	Hatchlings killed	Hatchlings surviving	Fire ants removed
2013	66	430	3,133	No
2015	68	36	2,746	Yes

2015, 52 fire ant colonies were removed in the vicinity of 14 different turtle nests (~21% of nests), with an average of nearly 4 fire ant colonies removed from the vicinity of each impacted turtle nest and a range of 1–14 RIFA colonies removed. Three of the 4 nests with dead hatchlings killed by fire ants were not treated for fire ants as no fire ant colony was detected in the vicinity of the turtle nest during visual searches. Thus, these RIFA colonies were likely missed during visual searches or new colonies appeared. For the fourth affected turtle nest, 3 colonies were removed but 10 hatchlings were still killed by fire ants, although 60 survived. As all other treated RIFA colonies did not kill any hatchlings, in sum this represents an approximate control rate of 98%.

Mortality of hatchlings, whether killed at pipping or once emerged from eggs, declined significantly between the 2013 and 2015 nesting seasons ($F_{1,132} = 7.71$, $P = 0.006$). On average, this represents 6.50 hatchlings killed per nest in 2013 versus 0.53 in 2015. Thus, for 2015, this represents a 67% reduction in fire ant predation of sea turtle nests, 91% fewer sea turtle hatchlings killed compared to 2013, and an overall reduction in mortality rate from ~14% of hatchlings killed by RIFA in the 2013 versus ~1% of hatchlings killed during 2015 when hot water treatments were applied. Of note, there was no significant difference in total hatchling survival between the 2 years ($F_{1,132} = 0.03$, $P = 0.859$; Table 1). On average, this represents 47.5 hatchlings surviving per nest in 2013 versus 40.4 in 2015, suggesting that RIFA may reduce hatchling survival, but factors other than RIFA predation probably exert a greater influence on fluctuations in number of hatchlings produced each year. No impacts upon sea turtle eggs or hatchlings of hot water treatment on RIFA colonies in the vicinity of sea turtle nests were detected.

In the wild population, fire ants were found within 10 m of all sparrow nests in 2017 and 2018. Across the 2 years, an average of nearly 6 (5.56) fire ant nests were removed from the 10-m radius search area around the sparrow nests (ranging from 1 to 16 fire ant nests) that were treated. In 2017, 1 of 9 treated FGSP nests succumbed to fire ant predation (89% control) and in 2018, 0 of 11 treated nests were affected (100% control). In 2017, 2 of the 4 FGSP untreated nests were lost to RIFA predation while in 2018, 0 of 5 untreated FGSP were lost to RIFA. For the sparrows, fire ant predation seems to result in an all or none outcome as nests that are attacked result in complete mortality of the chicks (typical clutch size is 3–5 chicks), whereas this may or may not occur with sea turtle nests. This is likely because sea turtle nests may contain many more individuals and thus some may escape fire ant predation, even if the nest is attacked.

Across the 2 years of treatment, FGSP survival was higher for RIFA-removed (treatment) FGSP nests than untreated (control) nests ($F_{2,16} = 4.36$, $P = 0.050$; Table 2). There was no significant effect of year ($F_{2,16} = 1.05$, $P = 0.319$) or an interaction of year and treatment ($F_{2,16} = 0.04$, $P = 0.84$). Multiple comparisons suggest that the significant effect of treatments approximately doubled the mean survival of FGSP nests over the 2 years (average number of surviving FGSP hatchlings of treated nests = 2.65 versus untreated = 1.38). Of note, in 2017 the one treatment FGSP nest that was lost to RIFA predation had 16 colonies removed in the vicinity of the nest. This was a very high density of RIFA colonies relative to most other nests and it is likely that one or more colonies survived removal treatment (or there were colonies missed during visual inspections).

No impacts of RIFA treatments on nesting sparrows were detected. Nests were treated while female sparrows were incubating eggs in all cases. Females remained on their nest during most treatments, and did not abandon nests upon approach, during treatments, nor after treatments. Thus, neither the noise of the hot water machine nor the physical movement and activities of treating nearby RIFA colonies led to nest abandonment.

At the 2 captive breeding facilities, where areawide control (elimination of all fire ant colonies) was enacted in 2017 and 2018, RIFA controls appeared to be very effective. In the larger north Florida site, a total of 511 colonies

TABLE 2 Number of nests and survival of Florida grasshopper sparrow (FGSP) hatchlings in 2017 and 2018, Florida, USA.

Year	FGSP nests	Surviving hatchlings	Fire ants removed
2017	9	12	Yes
2017	4	4	No
2018	11	29	Yes
2018	5	7	No

were removed (161 in 2017 and 350 in 2018). No nest mortality was attributed to RIFA predation of the captive breeding birds in those years (0% mortality). Four RIFA nests were removed from the smaller, south Florida breeding facility. No nest mortality was attributed to RIFA in that site, as well. Across all of the treated RIFA colonies (511) in the larger captive breeding site, the average time of water application was 2.8 min, and ranged from ~1–5 min (varying due to mound size and volume), suggesting that on average a volume of between 38–57 l (~10–15 gallons) of hot water was applied at a rate of ~19 l per minute. This represented approximately 21 hr of time spent treating 511 colonies. These treatments occurred over 4 site (~8 hour each) visits and included time to discover and flag colonies in the captive breeding area.

DISCUSSION

In sum, the results of this study suggested that low-pressure injection of hot water is an effective control of RIFA colonies in close proximity to ground nesting wildlife. Whether assessed by elimination of colonies or (more importantly) improved survival and reduced mortality of hatchlings, it is clear that the method is effective. Importantly, this establishes the method as a viable nontoxic control method for RIFA affecting ground-nesting wildlife. Application of the method in different habitats (beaches, open pasture) was successful, with ~90% or greater control rates of RIFA colonies, suggesting that this method can likely be adopted in a wide variety of ecosystems and for protection of a wide variety of ground nesting wildlife species that may be impacted by RIFA, TFA, and possibly other invasive ants. The effective control rate observed in this study is comparable to rates of control reported for RIFA using a variety of insecticides (Table 3; Middleton et al. 2023).

The low-pressure injection of hot water used here has important advantages over other water-based control methods such as hot water drenching and other methods of high-temperature applications (e.g., steam injection) that have been used in the past (Tschinkel and King 2007, King 2020*b*). First, the system is more efficient and effective at killing colonies. Typically, hot water drenching requires multiple treatments for almost every colony that is treated (Tschinkel and King 2007), whereas the injection method is effective on the first treatment most of the time (author, personal observation). This is likely because the injection system maintains much higher water temperature at the point of contact with ants as the system allows rapid delivery belowground, and the low-pressure application does not destroy much of the RIFA nest architecture, permitting rapid flooding of the entire belowground structure. Pouring water results in heat loss and inefficient delivery to the ants belowground (Tschinkel and King 2007, King 2020*b*). Second, the efficiency of the system permits rapid deployment and application when time spent on control and rapid elimination of problem RIFA colonies is important, such as during brief nesting periods of some wildlife. Third, the system design is flexible and easily transported to a variety of habitats as a self-contained system. This contrasts with the logistical issues of using fixed-point heating (a propane stove, for example) and a kettle to heat water which is limiting in the volume of water available and the logistics of heating the water and moving the equipment to where it is needed. Fourth, the system is safer and more effective than pouring buckets of hot water or generating steam (Tschinkel and King 2007, King 2020*b*).

TABLE 3 Reported results of representative fire ant control studies using different methods of local suppression or eradication of red imported fire ants.

Study	Control method	Environment	Plot size	Study duration (months)	Average number of mounds pre-treatment	Average number of mounds post-treatment	Maximum reported % reduction
Tschinkel and King (2007)	Hot water	Pasture (USA)	40 m × 40 m	36	35	2	94
This study	Hot water	Pasture/prairie various (USA)	Various	36	1–350	0–1	90–100
McNaught et al. (2014)	Methoprene,* pyriproxyfen,* hydramethylnon**	Suburban areas (Australia)	Various	11	22–5059 ha−1	0	100
Cook (2003)	Methoprene,* hydramethylnon**	Savanna/forest (USA)	2 ha	36	45	3	93
Collins et al. (1992)	Fenoxycarb,* hydramethylnon**	Pasture (USA)	0.4 ha	12	Not reported	Not reported	95–98
Barr (2005)	Various contact insecticides, toxicants, and growth regulators	Not reported (USA)	Not reported	8	25	1–6	76–96

*Insect growth regulators that disrupt metamorphosis, active ingredients in a variety of broadcast baits including Logic™ and Extinguish™.

**Metabolic inhibitor that disrupts cellular respiration, active ingredient in the broadcast bait Amdro™.

Given the advantages of the low-pressure, hot water injection system, the primary limitations are as follows: 1) it requires equipment, fuel, and access to water; 2) it requires training on the application technique and safe use of the equipment and there are safety considerations (high temperature water exposure, machinery with moving parts, and hot surfaces); 3) it is limited as a method for conducting areawide controls above ~1 ha or more as it would likely require too much time, fuel, and effort to successfully manage ants at that scale (Middleton et al. 2023); and 4) it requires at least some ability on the part of the user to identify and find invasive ant colonies. Colonies that were not treated or colonies that survived treatments were rare, given the total number of colonies treated, but are likely sources of mortality for hatchlings. Training in the discovery and identification of RIFA is not a serious limitation as there are very few mound-building ants that are easily confused in the field with *S. invicta*, and other studies (e.g., Middleton et al. 2023) have relied upon inexperienced and experienced personnel to detect fire ants with similar success. Training in the use of equipment is minimal and can be taught to an entirely inexperienced user in an hour or so (author, personal observation). Another potential limitation is the effect of high temperature water on nearby vegetation, although this has not yet been an issue for wildlife protection scenarios as elimination of RIFA colonies has not resulted in noticeable impacts on nearby vegetation when rechecked (author, personal observation). Even in cases, as in dune ecosystems, where RIFA were nesting at the base of plants, the plants survived treatments. It is most important to note that the levels of control reported for RIFA control in this study are comparable to levels reported for pesticides in other contexts (Table 3). In particular, the ability to immediately remove problem colonies and maintain local control at rates comparable to toxic baits, without the use of any pesticides, makes the hot water method a good option for many wildlife protection scenarios.

The cost of the equipment needed to assemble a trailer is variable and depends upon factors such as the vendor, whether the trailer is custom built by a fabricator or purchased from a manufacturer, and the size and type of components (e.g., a gasoline versus diesel motor, etc.) used in the build. In the US, current costs to purchase, license, and assemble a unit similar to the one used in this study may range from $3,000 to as high as $12,000 USD. Beyond purchase of the equipment, operating costs include fuel and maintenance. A diesel motor with a diesel burner (as used here) can operate on roughly 3.5–7.5 l (1–2 gallons) of fuel per 8-hr workday if used nearly continuously. Maintenance costs for the trailer used in this study averages around $300 USD per year with regular use. While a complete analysis of comparable costs for bait or contact insecticide (liquid spray) is beyond the scope of this paper, an approximate comparison of tractor- or ATV-applicators of bait (~$500–$3000) or spray (~$500–$5,000) and $13.50 USD per kg (~$30 per 5 pounds, granules with hydramethylnon active ingredient) for bait or ~$60 USD per 3.8 l (1 gallon) of liquid spray (e.g., bifenthrin active ingredient) shows that costs are not substantially different from the cost of the hot water machine, which had greater up-front costs, but over time the cost of baiting product or liquid insecticides can be high.

Time spent (labor) on application for any methods will vary enormously depending on habitat, access, and season. All control methods require regular site visits and application of the control method as the presence of fire ants throughout the landscape assures that sites left untreated will be recolonized (Drees and Gold 2003, Tschinkel 2006). Thus, this requires frequent reapplication of insecticides, if chemical controls are used, or visits with the hot water machine. The season that insecticides are applied can affect efficacy of chemical controls (Collins et al. 1992), often resulting in a need to reapply 2–3 times per year. However, it should be noted that in many wildlife protection scenarios where pesticide application is allowed but is not working (as in the sea turtle study herein) or pesticide application is not permitted (as in the Florida grasshopper sparrow study herein), cost comparisons may ultimately not be a determining factor as hot water management may be the only viable option for reducing impacts of RIFA.

Toxic baits for invasive ants are a relatively inexpensive and easily accessible option that should be considered as an option for wildlife protection scenarios, especially if there is a need for areawide treatment (many ant colonies over large areas). As the hot water method is entirely compatible with the use of attractive, toxic baits, (Plentovich et al. 2010; Hoffmann et al. 2011, 2016; Gaigher et al. 2012), specific invasive ant IPM programs can now be developed for wildlife and sensitive habitats. These programs can incorporate toxic bait application (Gaigher et al. 2012, Boser et al. 2017, Sakamoto et al. 2019, Epperson et al. 2021) for areawide controls as allowed and necessary as well as the use of hot water injection as a nontoxic option for rapid RIFA control near nesting wildlife.

Shortcomings in existing, pesticide-based IPM strategies should be considered along with the shortcomings and financial costs for the hot water injection when considering protection of ground-nesting wildlife. Beyond consideration of costs, managers should be aware that ineffective baiting may result from the lack of universally attractive baits and universally effective active ingredients (Hoffmann et al. 2011, Buczkowski 2021), as well as a variety of environmental conditions affecting active ingredient persistence and bait access by target organisms (Hoffmann et al. 2016).

Additionally, there are common nontarget effects that managers must consider in the context of protecting wildlife affected by invasive ants (Plentovich et al. 2010, 2011; Sakamoto et al. 2019). Other (nontarget) ants, roaches, and crickets are among the most commonly impacted nontarget insects groups affected by toxic baits (Tschinkel 2006; Plentovich et al. 2010, 2011; Sakamoto et al. 2019; Roeder et al. 2021). Introducing insecticides into arthropod food chains may be especially problematic if managers are trying to protect insect- and arthropod-feeding vertebrates like songbirds or some herpetofauna. Baiting also requires days or weeks to kill colonies and thus provides no relief for immediate removal of problem colonies that may, for example, affect individual vertebrate nests or nesting areas during critical nesting periods.

Baiting can create unexpected nontarget effects, such as attraction of opportunistic nest predators (racoons, crabs, rats, etc.) attracted to the carbohydrate or protein components of ant baits that are then better able to find and attack nearby wildlife nests (Smith et al. 2020). This may be especially true if baiting is used in excess of recommended application rates. Repeated baiting can also create ecological vacuums as the baits can eliminate native ants along with invasive ants that are potentially replaced by rapid recruitment and increased abundance (relative to pretreatment) of invasive ants, once the baiting is stopped (Stimac and Alves 1994, Morehart et al. 2022). Broadcast baits are also incompatible with many land use categories where ground-nesting wildlife needs protection. For example, there are limitations on their use in any areas where grazing occurs or in some scenarios where plants are being grown for human consumption. Application over very large areas may be cost-prohibitive and impractical for pesticides (Drees et al. 2013) or for areawide control using hot water (Middleton et al. 2023). Lastly, loss of efficacy can result if a target species is exposed to repeated, excessive baiting. This can result in the target species developing what appears to be bait-shyness, where worker ants no longer pick up or consume the bait (Bartlett and Lofgren 1961, Tschinkel 2006, Webb and Hoffmann 2013), although this is a poorly documented or understood phenomenon.

Collectively, the limitations of available methods to control invasive ants are still a potential barrier to effective mitigation of impacts on ground nesting wildlife. However, with the addition of the method described here, there is now a nontoxic option available for management that can complement existing pesticide-based programs and should be considered a viable management tool for invasive ants where pesticide application has proven insufficient protection or where pesticide application is not permitted.

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CONFLICT OF INTEREST STATEMENT

The author declares no conflicts of interest.

ETHICS STATEMENT

Sea turtle work at Fort DeSoto Park was authorized under permit FWC MTP-15-063. Florida Grasshopper work was authorized under the Assistant Regional Director—Ecological Services, Southeast Region, blanket permit, TE 697819-4. The author is the patent holder for the equipment and methods for controlling fire ants with hot water as described in this article.

DATA AVAILABILITY STATEMENT

Data are not yet provided. Data will be permanently archived if the paper is accepted for publication. Data will be submitted to Dryad.

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