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Analysis

Taking the sting out of Little Fire Ant in Hawaii

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ABSTRACT

In the 1990's, Little Fire Ants (LFAs) found its way to the island of Hawaii, most likely traveling with a shipment of potted plants from Florida. These plants were subsequently sold to consumers along the east coast of the Island, along with Little Fire Ant colonies living in the potting medium. LFA is now thriving and continues to spread. Fifteen years after the initial detection in 1999, LFA has spread to over 4000 locations on the island of Hawaii and has been found in isolated locations on Kauai, Maui, and Oahu Islands. Current efforts are expected to contain the infestations on the other islands but significant additional investment is needed to halt the rapid spread of LFA on the island of Hawaii.
Increased management expenditures can suppress infestations; reduce spread between sectors; and decrease long-term management costs, damages, and stings.

- An immediate expenditure of $8 million in the next 2–3 years plus follow-up prevention, monitoring, and mitigation treatments will yield $1.210 billion in reduced control costs, $129 million in lowered economic damages, 315 million fewer human sting incidents, and 102 million less pet sting incidents over 10 years.
- Over 35 years, the benefits include $5.496 billion in reduced control costs, $538 million less economic damages, 2.161 billion fewer human sting incidents, and 762 million fewer pet sting incidents.

1. Introduction

1.1. Problem Statement

Wasmannia auropunctata (roger), known as the Little Fire Ant (LFA), threatens native biodiversity, alters tropical ecosystems, impairs human health, impedes tourism, diminishes agricultural productivity, mars horticulture sales, and accordingly ranks among the world's worst invasive species (Lowe et al., 2000). Little Fire Ant will sting endangered reptiles and birds, interfering with reproduction, nesting, and survival of young. They also sting cats, dogs and other domestic animals in the eyes, blinding them over time (Theron, 2005). Humans are also stung by this species, both indoors and outdoors. The sting typically causes an intense burning sensation and painful itchy welts. Human habitats provide ideal niches for Little Fire Ant growth and survival (Krushelnycky et al., 2005). Human activities disperse Little Fire Ant quickly and widely.

1.2. Research Statement[1]

The purpose of this research is to assess the long term impacts of Little Fire Ant in Hawaii and to ascertain the economic and social benefit from greater public investment in prevention and control.

We developed a multi-sector, dynamic, stochastic, bioeconomic model to simulate LFA spread, human response, economic damages,

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[1] Abbreviations used in this article: LFA, HDOA.

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and social impacts. We parameterized the model with government data, primary survey data, and information from experts and practitioners. We specified several levels of management and simulated outcomes with Microsoft Excel using Frontline Risk Solver Platform©.

1.3. Background

Ants were first introduced when the Europeans settled the islands, in the 18th century. Hawaii is now home to 47 introduced ant species (Krushelnycky et al, 2005); with the recent introduction Little Fire Ant *W. auropunctata* regarded as potentially the most destructive. USDA-ARS (2010) estimate that total damages, losses and control costs attributed to invasive fire ants in the United States is $5.6 billion per year.

Little Fire Ant arrived on the island of Hawaii most probably in the 1990's and by the time the infestation was detected in 1999 (Conant and Hirayama, 2000), Little Fire Ant had spread to 13 separate locations. Aggressive control actions were undertaken immediately, however Little Fire Ant continued to spread (Conant, 2002) and by 2004, infested 31 locations (Fig. 1). In the years following its initial detection, Little Fire Ants have spread to three other islands in the Hawaii archipelago: Maui, Kauai (Vanderwoude et al., 2010) and Oahu in late 2013.

The source of Little Fire Ants found in Hawaii is most likely Florida USA. Little Fire Ants have an unusual form of reproduction. In introduced populations, almost all female reproductive offspring are genetically identical to the parent female and males are genetically identical to the male parent. This clonal form of reproduction allows the source of new invasive populations to be traced to the source population with a high degree of certainty. Foucaud et al. (2010) determined that the clonal lines of Little Fire Ants in Hawaii are identical to those of introduced populations in Florida USA.

Due to the severity and extent of impacts, LFA is considered among the world's worst invasive species (Lowe et al., 2000). In homes, schools, lodging, and parks, Little Fire Ant will sting adults, infants, children and pets. The reaction to stings varies from person to person. Some people experience a severe reaction with a great deal of pain and large raised welts that itch for a week or more. Babies can receive numerous stings within a few minutes of exposure. Pets are stung in the eyes and over several years lose their sight (Theron, 2005). Little Fire Ant infestations put agriculture crops and workers at risk (Fabres and Brown, 1978). When Little Fire Ant is present, aphid populations explode due to mutualism (Fasi et al., 2013) and farm workers are stung repeatedly. Plant nurseries can and have gone out of business due to lost productivity, high treatments costs, and a reluctance by consumers to buy infested stock. Wild honeybee hives in Hawaii have been swarmed and destroyed by LFA.

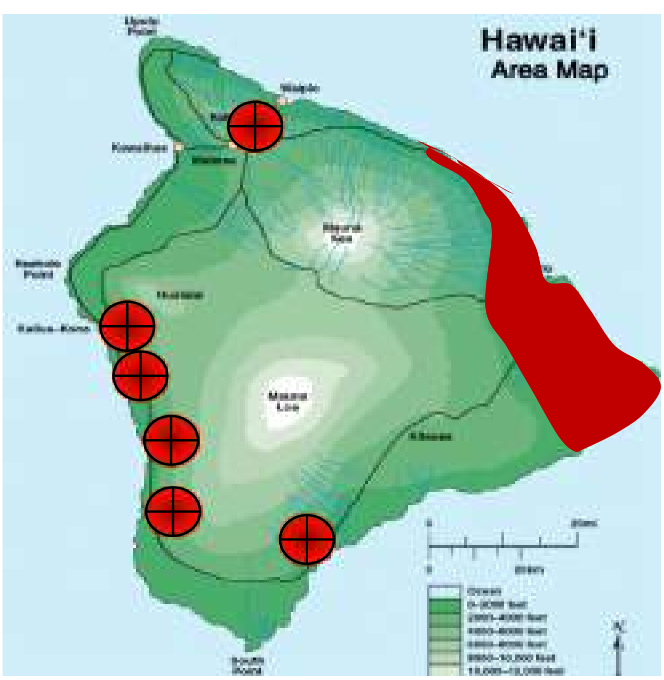

Fig. 1. Regions on Hawaii Island with one or more infested locations (red). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Once established, Little Fire Ant can occupy their habitat at an extraordinarily high density. Souza et al. (2008) estimate that total population size can exceed 200 million ants per hectare with worker:queen ratios of approximately 400 (Ulloa-Chacon and Cherix, 1990). This equates to a density of 20,000 ants per square meter, of which 40 will be queens.

Best-practice mitigation activities for affected residents and businesses comprise a regular (six weekly) application of granular baits to exterior areas combined with the use of residual pesticides both inside and on the exterior of structures. The Hawaii Ant Lab (University of Hawaii), with a staff of five people, provides research, outreach, education, training, advice and limited mitigation activities for all invasive ant issues in the state of Hawaii including maintaining a website[2] with information on impacts and remedies. The Big Island Invasive Species Committee provides education and outreach on Little Fire Ant and other invasive species on the island of Hawaii.

In modeling invasive species management, Mumford and Norton (1984) applied Bayesian decision theory to determine the timing and level of management as a function of the invasive species population density. Eiswerth and Johnson (2002) and Eiswerth and van Kooten (2002) incorporated dynamics to model population growth and uncertainty to allow for weather variability. To obtain closed-form solutions to the optimal invasive species management problem, Burnett et al. (2007), Carrasco et al. (2010), Mehta et al. (2007), Taylor and Hastings (2004), and Olson and Roy (2003) assumed a continuous rate of spread and employed optimal control modeling. Leung et al. (2002) modeled discrete invasive species spread employing stochastic dynamic programming.

Prevention management including monitoring invasion pathways associated with trade, transport and travel and inspecting potential vectors was modeled by Perrings (2005). Olson (2006) modeled invasive species introduction as a random variable and included prevention as a means to reduce the probability of introduction. Leung et al. (2002) specified prevention success as exponentially distributed and diminishing with effort. Mehta et al. (2007) indicated that prevention may do little to stop spread when the probability of introduction is small or when the number of invasion pathways is large, and modeled detection as a means of locating new introductions before they have had a chance to spread, where the probability of detection increases with the level of effort.

New introductions and established infestations require mitigation treatment in the form of chemical, mechanical, and manual means to reduce or eliminate the infestation. Treatment effectiveness as a stochastic process that decreases with effort was modeled by Feder (1979). The effectiveness of successive treatments was modeled with a cumulative probability distribution by Lichtenberg and Zilberman (1986). Olson and Roy (2003) used dynamic programming to determine the conditions under which eradication, mitigation, and no mitigation are optimal.

The marginal cost of invasive species management was modeled as a linear function that increased with the size of the infestation by Hastings et al. (2006) and Burnett et al. (2007); as a convex function by Olson (2006); and as a budget constrained function by Taylor and Hastings (2004), and Hastings et al. (2006). The marginal economic damage caused by the infestation was modeled as a linear function that

[2] www.littlefireants.com.

increased with the size of the infestation by Gutrich et al. (2007); as a quadratic function by Burnett et al. (2007); and as a non-linear function by Olson (2006) and Haight and Polasky (2010).

Leung et al. (2002), Burnett et al. (2007), and Eiswerth and van Kooten (2002) modeled invasive species population growth up to a carrying capacity over discrete time using a logistic function. Lee et al. (2007) modeled invasive species growth and spread overtime using a transition matrix to forecast the probability of uninfested locations becoming invaded, and then tracking that status of the infestation from incubating, to propagating, to spreading to other locations. Carrasco et al. (2010), Leung et al. (2002), and Burnett et al. (2007) simulated short distance dispersal via colony budding using a reaction–diffusion model. Suarez et al. (2001), Souza et al. (2008), and Wilson et al. (2009) modeled unlimited carrying capacity and long distance human mediated dispersal. Nathan et al. (2003) used gravity models to quantify human-mediated long distance dispersal. Hastings et al. (2005), and Bossenbroek et al. (2001) used commerce and traffic flows to model human-mediated dispersal pathways. Carrasco et al. (2010) assumed outward dispersal via a random walk process and used diffusion models. Eiswerth and van Kooten (2002), Kot and Schaffer (1986), Hastings et al. (2005), and Law et al. (2003) employed a probabilistic transition function[3] to model dispersal. Scanlan and Vanderwoude (2009) modeled dispersal using a stochastic cellular automata.

2. Materials and Methods

2.1. Model Framework

We simulate future spread and impacts from LFA on the island of Hawaii using a bioeconomic model comprised of three integrated sub-models: impact, management, and spread. Control variables determine the level of effort allocated toward LFA detection, spread prevention, and mitigation treatment.

2.1.1. Impacts

The impact sub-model quantifies economic impacts (economic damage and management expenditure) and social impacts (the number of human and pet LFA sting incidents) per sector over time. Economic damages are sector dependent and vary with the size and extent of the infestation. Management expenditures are based on best management practices and current technology and vary with management goals, management effort, and the cost of labor and materials. Sting incidents are based on the number of infested locations in each sector, human population, pet population, demographics, and employment in each sector. A sting "incident" may involve multiple LFA stings.

2.1.2. Management

The management sub-model quantifies the effect of management decisions on LFA survival, growth and dispersal. Management activities include detection, prevention, and mitigation treatment. Detection allows new infestations to be treated before they become established. Prevention reduces the likelihood that LFA will be transported to another location by humans. Mitigation treatments reduce the intensity and extent of infestations.

2.1.3. Spread

The spread sub-model simulates LFA survival, growth and dispersal as follows. When LFAs are initially introduced to a new location their chance of surviving is low. If they survive, they go unnoticed for several years during which they have time to establish and increase in number. The first year after introduction, LFAs are comparatively easy to eradicate. Once they establish, they are difficult to eradicate, begin causing damage, and start producing new colonies that can be transported to other locations.

2.1.4. Original Contribution

In previous models of invasive ants, spatial spread was forecast using radial and cellular specifications. Our approach is novel in that we model LFA spread within and across economic sectors over time. On the island of Hawaii, LFAs are transported unintentionally by humans with the movement of infested soil, produce, and other goods; mechanisms which do not follow a radial or cellular pattern. Further, LFA nests are tiny compared with the area they can impact; several tiny walnut-sized nests can disrupt the activities of an entire household or farm. Thus rather than units of length or area, we use discrete locations as our unit measure of "space", e.g. a home, a school, a farm, and a park. One unit represents one location. This pseudo-spatial approach provides us with a compact way of specifying and simulating the joint relationships between economic activity, LFA movement, LFA impacts (economic and social), and management response. Our second contribution is an accounting of the number of LFA stings and a comparison of the Pareto tradeoff between economic impacts and stings.

2.2. Model Scope and Detail

Our model includes ninety thousand locations on the island of Hawaii within seven economic sectors $i \in$ {nursery, agriculture, lodging, residential, parks, schools, and all others}. Of the ninety thousand locations, 4581 locations are infested initially. Our model simulates infestation 35 years $t \in \{0\ldots35\}$ into the future. The number of locations per sector and initial LFA infestation is shown in Table 1.

2.2.1. Impacts

Impacts from LFA comprise economic damages, management costs, and human and pet sting incidents.

2.2.1.1. Economic Damages. Economic damages are sector-specific and vary with the size and extent of the LFA infestation. For example, in the residential sector we include the impact of LFA on property values when homes are sold. In the lodging sector we include reduced revenues from decreased room occupancy and cheaper room rates. The economic damage per sector location is based on estimated mean economic impacts from LFA and is assumed to increase with the number of infested locations and overall level of infestation. The economic damage in sector i at time t is:

$$D_{i,t} = c_i^{damage} \frac{{N_{i,t}^{establish}}^2}{N_i^{max}}. \quad (1)$$

Table 1
Little Fire Ant infested locations on the island of Hawaii in 2012.

Sector	% Infested	Infested locations	Total locations
Nursery	22.5%	170	757
Agriculture	4.0%	186	4650
Lodging	0.2%	1	468
Residential	7.0%	3648	52,216
Parks	3.9%	6	152
Schools	1.2%	1	84
Other	1.7%	568	32,547[a]
Total	5%	4581	90,874

From Motoki et al. (2013).[b]

[a] Hawaii Island is 2.58 million acres. With our 6 major sectors we account for 2.3 million acres. Our sector "other" consists of 0.28 million acres and 81,556 parcels (according to 2010 tax records). To scale the model, we represented the "other" sector with 32,547 locations.

[b] Using data from the Hawaii Ant Lab; information from the 2007 Census of Agriculture, the 2011 Visitor Plant Inventory, City-data.com, and the State of Hawaii Data Book, and 2013 PCSU Technical Report #186.

[3] A transition matrix is a kernel without a functional form, matrix elements denote the probability of transitioning between states or spatial locations.

Here c_i^{damage} is the average economic damage at locations where LFA has become established, $N_{i,t}^{establish}$ is the number of locations where LFA has become established in sector i at the end of time t; N_i^{max} is the number of locations in sector i that are susceptible to LFA. Thus, when sector i becomes fully infested, $N_{i,t}^{establish} = N_i^{max}$ and annual damage is $c_i^{damage} N_i^{max}$.[4]

For agricultural impacts we estimated yield loss to untreated crops. Agricultural damages are $600 per farm. For nursery impacts we estimated revenue losses due to banned exports. Nursery damages are $9000 per farm. For residential impacts we estimated reduced property values when the homes are sold. Residential damages are $1000 per property. For lodging impacts we estimated revenue losses due to reduced visitation and lowered rates. Lodging damages are $183,000 per property. For park impacts we attempted to capture ecosystem productivity losses due to destruction of wild bee hives and increased chick mortality of ground nesting birds. Using cost transfer methods, park damages are $2300 per acre. For "other" sector impacts we surveyed landowners and businesses to find out the most they would spend on LFA mitigation. "Other" sector impacts are $500 per location.[5]

2.2.1.2. Management Expenditures. Management cost parameters are based on current technology, best management practices, and current costs for materials and labor. Total management expenditure is a function of management goals, management decisions, and size of the managed area. Management activities include prevention, detection, and mitigation.

Prevention expenditure is proportional to the number of infested locations. Prevention expenditure $c^{prevent}$ is a function of unit cost $p_i^{prevent}$, number of known infested locations $N_{i,t}^{known}$ and prevention effort $d_{i,t}^{prevent}$ as follows:

$$c_{i,t}^{prevent} = p_i^{prevent} N_{i,t}^{known} d_{i,t}^{prevent}. \tag{2}$$

Detection (monitoring) expenditure is proportional to the number of uninfested locations. Detection expenditure is a function of the unit cost of detection per location $p_{i,t}^{detect}$, number of uninfested locations $(N_i^{max} - N_{i,t}^{known})$, and detection effort $d_{i,t}^{detect}$ as follows:

$$c_{i,t}^{detect} = p_{i,t}^{detect} \left(N_i^{max} - N_{i,t}^{known} \right) d_{i,t}^{detect}. \tag{3}$$

Mitigation treatments are applied to known infestations. Mitigation expenditure $c^{mitigate}$ is a function of unit cost of mitigation $p_i^{mitigate}$, number of infested location $N_{i,t}^{known}$, and mitigation effort $d_{i,t}^{mitigate}$ as follows:

$$c_{i,t}^{mitigate} = p_i^{mitigate} N_{i,t}^{known} d_{i,t}^{mitigate}. \tag{4}$$

Expenditures for mitigation treatments, prevention, and detection are summed to obtain total management expenditure in sector i at time t as follows:

$$M_{i,t} = c_{i,t}^{prevent} + c_{i,t}^{detect} + c_{i,t}^{mitigate}. \tag{5}$$

2.2.1.3. Total Cost. Economic damage $D_{i,t}$ and management expenditure $M_{i,t}$ are discounted and summed over time t to obtain an expression of the present value future total cost associated with LFA infestation:

$$Total\ Cost = \sum_{t=0}^{35} \delta_t \left(\sum_{i=1}^{7} D_{i,t} + M_{i,t} \right) \tag{6}$$

where $\delta_t = 1/(1+r)^t$ is the discount factor, r is the annual discount rate, and i indexes the seven economic sectors: agriculture, nursery, residences, schools, lodging, parks, and all others.

2.2.1.4. Social Impacts. LFA stings cause extreme pain, high anxiety, and itchy welts. While other species of fire ants nest solely outdoors and on the ground, LFA will enter houses, nest under kitchen counters and in bedding, and crawl beneath clothing to sting people in their homes. Outdoors, LFA can nest in leaf litter, in bushes, and in trees dropping onto people who happen to brush by. Each encounter with LFA may entail multiple stings. Domestic animals and pets are particularly susceptible to LFA stings. In infested residential areas, LFAs have repeatedly stung cats and dogs in the eyes inevitably blinding the animals over time.

We used Census data (DEBDT, 2012a) and forecasts (DEBDT, 2009) to estimate human population at home and at work (DEBDT, 2012b) by sector. We used tourism authority data to estimate daily visitor counts (HTA, 2012). We used U.S. pet statistics to estimate the population of domestic pets (cats and dogs) on the island of Hawaii (AVMA, 2012). We combined human and pet population data with our spread model infestation rates to compute sting incidents to adults and children at home and at play, adults at work, children at school, and visitors at lodging and at play. Using infestation in the residential sector, we estimated the number of sting incidents to domestic pets in homes.

The number of LFA sting incidents per year $S_{i,t}$ is dependent on the human population $Pop_{i,t}$, the level of infestation, $\frac{N_{i,t}^{establish}}{N_i^{max}}$, and the daily probability of being stung in an infested area $\lambda_{i,t}^{sting}$, multiplied by the number days per year:

$$S_{i,t}^{human} = \lambda_{i,t}^{sting} N_{i,t}^{establish} \left(\frac{N_{i,t}^{establish}}{N_i^{max}} \cdot Pop_{i,t} \right) 365. \tag{7}$$

Over 35 years, *total human sting incidents* is:

$$Total\ human\ sting\ incidents = \sum_{t=0}^{35} \sum_{i=1}^{7} S_{i,t}^{human}. \tag{8}$$

Working conditions and land-use characteristics are all used to determine the sting incident rate $\lambda_{i,t}^{sting}$. For example, nursery workers who are in constant contact with plants will typically be stung more frequently than hotel workers. Sting incident frequency increases with the extent of LFA infestation. We quantified LFA sting incidents to humans based on estimated number of human sting incidents that would occur at homes, at work, in parks, at lodging, and at schools. We used population data on residents, work force, and visitors.

The number of pet sting incidents per year is dependent on the number of domestic dogs and cats Pop^{pets}, pet sting incident frequency per day λ^{pets} and level of infestation in the residential (homes) sector:

$$S_t^{pet} = \lambda^{pets} Pop_t^{pets} N_{i,t}^{establish} \left(\frac{N_{i,t}^{establish}}{N_i^{max}} \right) \cdot 365. \tag{9}$$

LFA human and pet stings are a major social concern. For this study, we enumerate the number of sting incidents without monetizing them to allow the frequency of stings to be considered separately from economic impacts

2.2.2. Management Decisions

Based on level of infestation, management goals and constraints, we use the model to determine investment in prevention, detection, and mitigation by sector and time period. Investment in detection increases the likelihood of finding LFA at newly introduced locations before the infestation becomes established. Investment in prevention reduces the

[4] The form of this equation is similar to Mehta et al. (2007).
[5] About $50/acre per year.

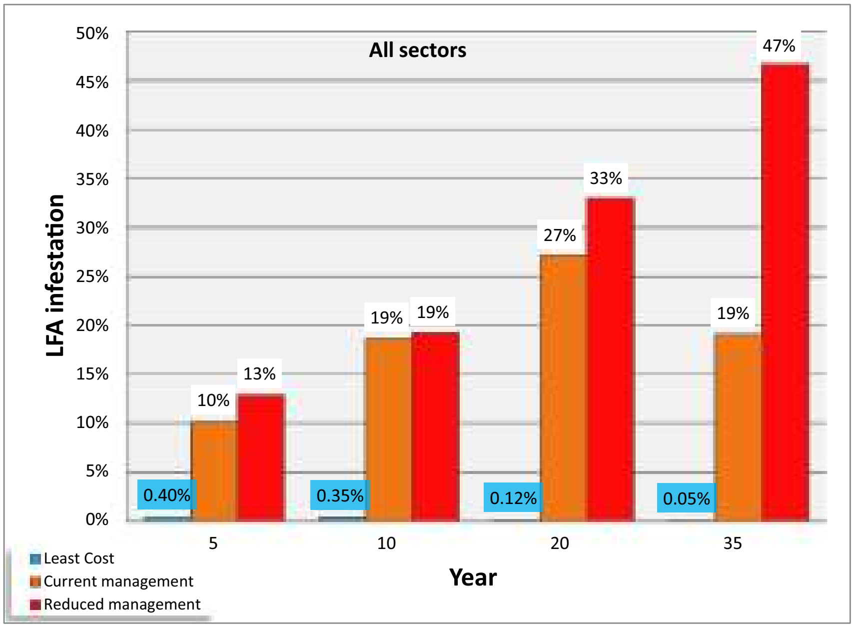

Fig. 2. Little Fire Ant Infestation by management type and year across all sectors.

probability that LFAs are transported between locations. Investment in mitigation reduces the level of infestation at established locations.

2.2.2.1. Decision Variables. The decision (control) variable, $d_{i,t}^{(\ldots)}$, determines the level of effort in prevention, detection, and mitigation in each sector i at each time period t. Prevention and detection activities are non-negative and unbounded, i.e., $d_{i,t}^{prevent}$, $d_{i,t}^{detect} \geq 0$. Mitigation treatment is nonnegative and bounded where $0 \leq d_{i,t}^{mitigate} \leq 4$.

2.2.2.2. Effectiveness. LFAs are elusive and as a result management activities are imperfect. The annual probability that any management activity (prevention, detection, or mitigation) will succeed is less than one. We model management success with a geometric distribution. Where λ is the probability of success (e.g. preventing a new infestation at one location). For $d \leq 1$, the probability of success is $\theta = 0$, for $d \geq 1$, and the probability of success is:

$$\theta = 1-(1-\lambda)^{d} \tag{10}$$

where $0 \leq \lambda \leq 1$ and $0 \leq \theta \leq 1$.

Prevention encompasses efforts to thwart new infestations by reducing movement of LFA between locations. Prevention effectiveness $\theta_{i,t}^{prevent}$ depends on the probability of stopping spread $\lambda_i^{prevent}$ and the investment in prevention $d_{i,t}^{prevent}$:

$$\theta_{i,t}^{prevent} = 1-\left(1-\lambda_i^{prevent}\right)^{d_{i,t}^{prevent}}. \tag{11}$$

Prevention investment $d^{prevent} \in [0, \infty)$ is in units of person-hours per sector per year and $\lim\limits_{d^{prevent}\to\infty}\left(\theta_{i,t}^{prevent}\right) = 1$.

Monitoring for LFA increases the likelihood that newly introduced LFA colonies are found before they can establish, grow, and spread. Detection effectiveness θ_i^{detect} depends on the probability of detecting an LFA infestation λ^{detect} and investment in detection $d_{i,t}^{detect}$ [6]:

$$\theta_{i,t}^{detect} = 1-\left(1-\lambda_i^{detect}\right)^{d_{i,t}^{detect}}. \tag{12}$$

Detection investment $d_{i,t}^{detect}$ is in units of person-hours per sector per year and $\lim\limits_{d^{detect}\to\infty}\left(\theta_{i,t}^{detect}\right) = 1$.

Mitigation reduces the number of infested locations within a sector. Here mitigation effort is measured in terms of the number of insecticide applications $d_{i,t}^{mitigate}$ per sector per year.[7] Each application eradicates LFA with probability $\lambda_i^{mitigate}$ such that

$$\theta_{i,t}^{mitigate} = 1-\left(1-\lambda_i^{mitigate}\right)^{d_{i,t}^{mitigate}} \text{ and } \lim_{d^{mitigate}\to 4}\left(\theta_{i,t}^{mitigate}\right) = \hat{\theta}. \tag{13}$$

Management effort effectiveness parameters are derived from recommended best management practices and expert opinion.

2.2.3. Infested Locations and Spread

The initial infestation $N_{i,0}^{start}$ is set equal to the number of LFA infested (established) locations in 2012 as shown in Table 1. The spread submodel simulates the survival, growth, and dispersal of LFA over time within and between economic sectors. With this pseudo-spatial representation, we simulate LFA spread as occurring with the movement of goods and people over time within and across sectors. With information on acres per unit (location) and units per sector, we estimate infested acreage over time as follows: at each newly infested location the status transitions from "introduced" to either "uninfested" or "incubating[8]" and then to "uninfested" or "incubating" or "established." The model tracks the number of locations N in sector i at time t for each state of infestation $(\ldots)$ *as* given by $N_{i,t}^{(\ldots)}$ a whole number value that cannot exceed the number of locations per sector defined here as: $N_{i,t}^{(\ldots)} \geq 0$ and $\sum\limits_{(\ldots)} N_{i,t}^{(\ldots)} \leq \tilde{N}_i^{max}$.

2.2.3.1. Incubation, Detection, Mitigation. During incubation, LFAs reproduce but do not spread. The number of locations with incubating populations equals the number of locations infested from other sectors $N_{i,t}^{introduced}$ plus the number of locations infested internally $N_{i,t-1}^{growth}$. While incubating, LFA can be detected with effectiveness θ^{detect}. The

[6] This formulation of early detection is a modification of the functional form put forth by Carrasco et al. (2010).

[7] Insecticide application frequency is limited to 4 times per year per the manufacturer's instructions.

[8] Nascent.

number of locations with newly introduced ($w = 1$) incubating infestations that escaped detection is defined:

$$N_{i,t,w}^{incubate(unk)} = \left(N_{i,t}^{introduced} + N_{i,t-1}^{growth}\right)\left(1-\theta_{i,t}^{detect}\right). \quad (14)$$

The number of newly introduced incubating infestations that have been detected ($w = 1$) is defined:

$$N_{i,t,w}^{incubate} = \left(N_{i,t}^{introduced} + N_{i,t-1}^{growth}\right)\theta_{i,t}^{detect}. \quad (15)$$

Incubating infestations can be destroyed with probability $\lambda = 1$, so the decision to eradicate is $d = (0, 1)$. If $d_{i,t}^{eradicate} = 1$ then the $N_{i,t,w}^{incubate} = 0$ If $d_{i,t}^{eradicate} = 0$ the number of known locations with incubating populations is defined: Incubating infestations become established after 3 years. The number of locations with established LFA populations is defined:

$$N_{i,t+1,w+1}^{incubate} = N_{i,t,w}^{incubate}\left(1-d_{i,t}^{eradicate}\right) \quad (16)$$

$$N_{i,t}^{establish} = N_{i,t-1}^{establish} + N_{i,t-1,3}^{incubate} + N_{i,t-1,3}^{incubate\ (unk)}. \quad (17)$$

All established infestations are assumed to be "known" infestations due to the damages they cause and are thus candidates for mitigation treatment. The effectiveness of treatment $\theta^{mitigate}$ is defined in Eq. (13). The number of locations with established LFA colonies is defined:

$$N_{i,t}^{establish} = N_{i,t-1}^{establish}\left(1-\theta_{i,t}^{mitigate}\right). \quad (18)$$

The number of infested locations in each sector i is:

$$N_{i,t+1}^{final} = N_{i,t}^{establish} + N_{i,t}^{incubate} + N_{i,t}^{incubate(unk)}. \quad (19)$$

2.2.3.2. Human Transport. Through human movement (to and from work, school, and outdoor recreation) and goods exchange, live viable ant colonies are dispersed among and between sectors.

Viable ant colonies transported out of one sector to another sector is termed an Outgoing propagule. The number of Outgoing propagules $N_{i,t}^{out}$ is proportionate $\lambda_i^{invasion}$ [9] to the number of infested locations $N_{i,t}^{establish}$ less the effectiveness of prevention efforts $\theta_{i,t}^{prevent}$ and is expressed as follows:

$$N_{i,t}^{out} = N_{i,t}^{establish}\lambda_i^{invasion}\left(1-\theta_{i,t}^{prevent}\right). \quad (20)$$

Viable ant colonies transported into one sector from other sectors are termed Incoming propagules $N_{i,t}^{in}$. Incoming propagules are the sum of Outgoing propagules $N_{j,t}^{out}$ transported from all other sectors $j \neq i$, defined as follows:

$$N_{i,t}^{in} = \left(\sum_{j}^{n} k_{j,i} \cdot N_{j,t}^{out}\right)\left(1-\frac{N_{i,t}^{growth}}{N_i^{max}}\right). \quad (21)$$

The matrix K captures the commerce on the island likely to transport ant colonies between sectors. The matrix elements $k_{j,i}$ are nonnegative $0 \le k_{j,i} \le 1$ with values that sum to one $\sum_{j}^{n} k_{j,i} = 1$. Uninfested and less infested sectors are assumed more susceptible to incoming propagules than heavily infested sectors hence inclusion of the factor $\left(1-\frac{N_{i,t}^{growth}}{N_i^{max}}\right)$.

[9] Termed "base rate invasion probability" (Leung et al., 2002).

Table 2
Little Fire Ant Infestation by sector in years 5 and 35.

Sector	Year 5			Year 35		
	Least cost	Current management	Reduced management	Least cost	Current management	Reduced management
Ag	1%	5%	7%	0.2%	19%	30%
Lodging	5%	50%	54%	0.4%	56%	67%
Nursery	1%	31%	39%	0.2%	43%	56%
Other	1%	8%	9%	0.1%	15%	23%
Parks	0%	60%	60%	0.1%	56%	66%
Residential	0%	11%	15%	0.0%	21%	32%
Schools	24%	52%	64%	0.2%	45%	57%

Percent infested.

Of the incoming propagules only a proportion $\lambda_i^{survive}$ survive to become newly introduced infestations:

$$N_{i,t}^{introduced} = \lambda^{survive} N_{i,t}^{in}. \quad (22)$$

2.2.3.3. Intrinsic Growth. For our model, we define intrinsic growth as viable ant colonies crawling from one location to another. For LFA, the rate of intrinsic growth λ^{growth} is slow.[10] We simulate intrinsic growth as increasing in the number of established locations $\lambda^{growth} N_{i,t}^{establish}$ and decreasing as the sector approaches full infestation. The number of locations newly infested from intrinsic growth is defined:

$$N_{i,t}^{growth} = \lambda^{growth} N_{i,t}^{establish}\left(1-\frac{N_{i,t}^{establish}}{N_i^{max}}\right). \quad (23)$$

3. Management Scenarios

To assess the potential economic damages from Little Fire Ant on the island of Hawaii and potential benefits from managing Little Fire Ant, we evaluated a current management (status quo) scenario and two alternate scenarios: reduced management (a reduction in public management efforts to contain infestations and prevent spread) and least cost (a theoretical Pareto optimum that assumes perfect knowledge and full cooperation; the sum of management costs and economic damages is minimized).

Current public management is led by the Hawaii Ant Lab (University of Hawaii). With a staff of five people, the Lab provides research, outreach, education, training, advice and limited mitigation activities for all invasive ant issues in the State of Hawaii including maintaining a website[11] with information on impacts and remedies. The Big Island Invasive Species Committee provides education and outreach on Little Fire Ant and other invasive species on the island of Hawaii.

For the current management scenario, we assumed that residents and businesses with LFA infestations treat periodically to mitigate local impacts but not sufficiently to eradicate LFA from their property or halt the spread to other properties. Treatment occurs when infestation reaches 20%, then control effort is proportionate to the level of infestation. In the Park and School sectors, LFA infestations remain untreated.[12]

For the reduced management scenario, we assumed a cut in public funding for mitigation treatment, prevention, detection, outreach and education which would result in a faster rate of spread. Residents and businesses with LFA infestations treat periodically to mitigate local impacts but not sufficiently to eradicate LFA from their property or halt the spread to other properties. Treatment occurs when infestation

[10] Ten meters per year.

[11] www.littlefireants.com.

[12] At present, infested public schools and parks are being treated for LFA. However, when this study began, schools were not treated due to lack of funding and parks were not treated because use of anticides was not permitted.

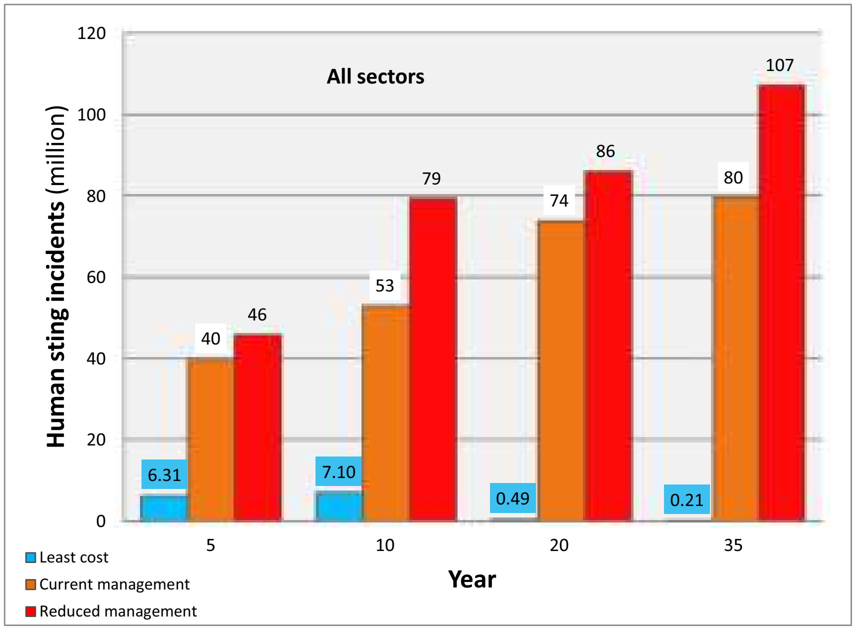

Fig. 3. Little Fire Ant human sting incidents by management type and year across all sectors.

reaches 20%, then control effort is proportional to the level of infestation. In the Park and School sectors, LFA infestations remain untreated.

For the least cost management scenario, we assumed that treatment decisions in all sectors were made to benefit the whole island without regard to distributional effects.

We applied simulation modeling to determine the long-term impacts from current management and reduced management.[13] We applied optimization modeling to determine the cost minimizing decisions and long term impacts from least cost management.

The model was run on Microsoft Excel using the Frontline Risk Solver Platform.

4. Results

4.1. Current Management

Under current management in the coming 5 years, Little Fire Ant will spread on the island of Hawaii infesting 31%, 50%, 60%, and 52% of the nursery, lodging, park, and school sectors. In 10 years, infestation will reach 42% and 54% in the nursery and lodging sectors. In 35 years, the present value total cost from Little Fire Ant is $6.1 billion based on $5.536 billion management expenditures and $549 million in economic damages. Costs are greatest in the agriculture, park, and school sectors. Over 35 years, the total number of Little Fire Ant sting incidents involving children, adults and visitors is 2.3 billion.

4.2. Least Cost Management

To achieve least cost management, Little Fire Ant is suppressed with early mitigation treatment; prevention and detection in all infested sectors. Under least cost management in the coming 5 years, Little Fire Ant infestations decrease to 5% and 24% in the lodging and school sectors, drop to 2.5% in the nursery and lodging sectors, and sink to 1% or lower in the remaining sectors. Over 35 years, the present value total cost is $51 million based on an estimated $40 million in management expenses and $11 million in damages. Mitigation expenditures are greatest in the agriculture and school sectors. Prevention expenditures are greatest in the residential sector. Detection expenditures are greatest in the lodging sector. Over 35 years, the total number of Little Fire Ant sting incidents involving children, adults and visitors is 94 million.

4.3. Reduced Management

Under reduced management, in the coming 5 years, Little Fire Ant will spread more quickly on the island of Hawaii infesting 53%, 66%, 71%, and 54% of the nursery, lodging, park, and school sectors. In 10 years, infestation will reach 57%, 71%, 74% in the nursery, lodging, and park sectors. Mitigation expenditures are greatest in the agriculture, park, and school sectors. The number of sting incidents is highest in the residential sector. In 35 years, the present value total cost including management expenditures and economic damages from Little Fire Ant is $12.9 billion. Over 35 years, the total number of Little Fire Ant sting incidents involving children, adults and visitors is 2.8 billion.

Simulation model results for infestation over time by sector and management type are illustrated in Fig. 2 and Table 2.

Simulation model results for human sting incidents over time by sector and management type are illustrated in Fig. 3 and Table 3.

Simulation model results for total cost over time by sector and management type are illustrated in Fig. 4a–c.

4.4. Management Tradeoffs

We conducted a multi-objective analysis to evaluate the tradeoff between management focused on reducing the monetary cost of an LFA infestation (management expenditures and damages) versus management focused on reducing the number of human sting incidents. If cost reduction is the primary objective, a least cost management strategy will yield a PV total cost of $51 million and 94 million human sting incidents over 35 years. This outcome is a clear improvement over current management,[14] as both cost and human sting incidents are reduced. This outcome is "efficient" because in order to further reduce

[13] We applied simulation modeling. For interested readers, a comparable problem solved with constrained optimization would minimize LFA spread subject to a public budget of $200k to depict current management and minimize LFA spread subject to an annual budget of $100k to depict reduced management.

[14] Under current management PV total cost is $6.1 billion and total human sting incidents is 2.3 billion over 35 years.

Table 3
Little Fire Ant human sting incidents by sector in years 5 and 35.

Sector	Year 5			Year 35		
	Least cost	Current management	Reduced management	Least cost	Current management	Reduced management
Ag	0.01	0.03	0.05	0.00	0.26	0.41
Homes	0.00	8.46	11.11	0.00	25.24	38.79
Lodging	0.74	6.79	7.29	0.10	14.33	17.35
Nursery	0.01	0.23	0.30	0.00	0.59	0.76
Other	0.14	1.50	1.76	0.03	4.97	7.81
Parks	0.07	11.27	11.24	0.02	17.80	21.22
Schools	5.34	11.58	14.02	0.06	16.34	20.87

Million sting incidents.

costs, sting incidents would have to rise. If reducing human sting incidents is the primary objective, a least sting management strategy will cost $91 million and reduce human sting incidents to 73 million over 35 years. This outcome is a clear improvement over current management, as both cost and human sting incidents are reduced. This outcome is “efficient” because in order to further reduce sting incidents costs would have to rise. For example, reducing human sting incidents to 22 million will cost $140 million over 35 years for a marginal cost of $3 per human sting incident avoided. Reducing human sting incidents to 6 million will cost $944 million over 35 years for a marginal cost of $306 per human sting incident avoided. Additional numerical results from the multi-objective analysis can be seen in Table 4.

If society places a high value on avoiding sting incidents, i.e. not getting stung, they may be willing to invest more in LFA management and treatment. Information on marginal costs can help individuals determine their preferred level of LFA control. At higher costs, individuals may prefer to be stung rather than pay for the additional management. Efficient alternatives for the island of Hawaii range from $2 to $306 per avoided sting incident. Values are displayed in Table 4 and illustrated in Fig. 5.

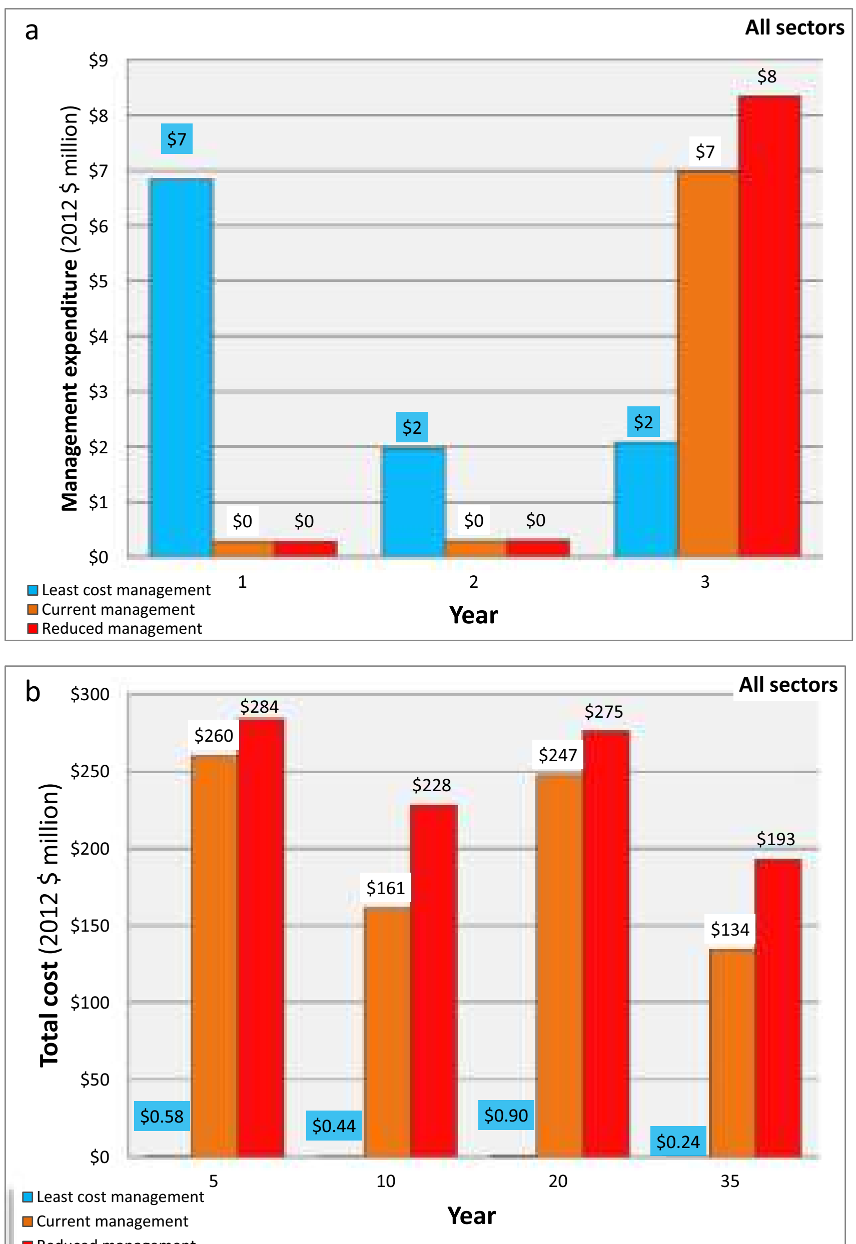

Fig. 4. a. Early management expenditures by year and management type. b. Economic cost to society by year and management type. c. Little Fire Ant total economic cost over 35 years by management type.

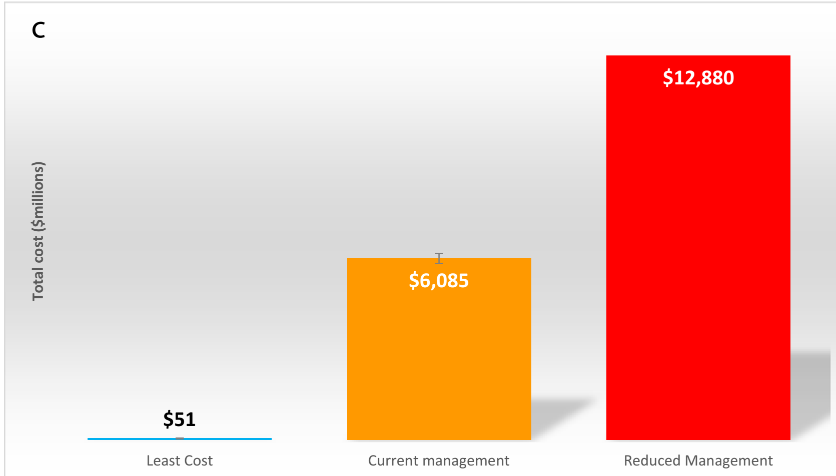

Fig. 4 (*continued*).

5. Discussion of Results

Our model results showed that an increase in funding over current management will be needed to prevent rapid and widespread infestation of Little Fire Ant on the island of Hawaii.

The benefits from increased management effort include:

- Improved quality of life for residents, children, and pets.
- Savings to homeowners from less frequent treatment of LFA in and around the home.
- Protection to agricultural and nursery farms from large increases in expenses and potential economic losses due to yield decline, treatment costs, lost sales, and reduced export volume.
- Protection to visitor industry businesses from large increases in expenses and potential economic losses due to visitor sting incidents on lodging property and at popular outdoor recreation areas.
- Reduced risk of spread from the island of Hawaii to other islands in the State.

Technical challenges in managing little fire ant on the island of Hawaii include:

- Newly developed bait formulations and application methods are proving effective in controlling LFA populations. However their use in commercial agriculture is banned except for a few food crops.
- LFAs are thriving in beach parks, but until recently no chemical options were permissible for use at infested locations near water.

Economic Challenges and Opportunities

- Treating a widespread infestation of LFA will require a high level of cooperation from all agents including property owners, farms, businesses, and multiple levels of government. In our model, we assumed full cooperation, but in reality that is not be the case. We've heard several complaints from distressed homeowners and farmers about LFA infestations on neighboring properties that are left untreated.
- At the private level, individual households and businesses will pay to control LFA on their own property hence benefiting their neighbors, however since they do not share in those additional benefits, they will then tend to underinvest in LFA control, perhaps not treating the periphery of their property or otherwise leaving more ants than optimal to reproduce and spread (Positive externality).
- The location of new infestations is difficult to predict. To a large extent, the State relies on an observant public to report new infestations — detection through use of peanut butter sticks, visual observations, or receiving stings (Imperfect information).
- Infested businesses may treat for LFA but be unwilling to report their infestation to avoid repercussions such as loss in customers, ban on sales, lost certification, and quarantine (Asymmetric information).
- Neighborhoods, communities, and businesses within the same industry can share information, treatment methods, and costs, and benefit as a group from managing LFA collectively. Coordinating a group effort requires a lot of communication, time, and willing volunteers (Information costs, scale economies, positive externalities).

6. Conclusions

On the island of Hawaii, Little Fire Ant infests over 4000 locations. Current management includes ant species identification, response, public information and assistance, technology development, public awareness and education. Our findings show that current management is slowing Little Fire Ant spread but will be insufficient in preventing Little Fire Ant from rapidly spreading within the island of Hawaii. Reducing efforts to control Little Fire Ant will lower costs in the short term compared with current management, but lead to more sting incidents,

Table 4
Total cost and total human sting incidents over 35 years.

PV total cost	Human sting incidents	Marginal cost per avoided sting incident[a]
$ mil	*mil*	*$*
$51	94	–
$91	73	$2
$140	22	$3
$153	18	$4
$159	17	$5
$166	15	$6
$174	14	$7
$183	13	$9
$194	12	$12
$207	12	$16
$225	11	$24
$254	10	$41
$300	9	$56
$388	8	$83
$944	6	$306

[a] Marginal cost is calculated as Increase in total cost ÷ Reduction in sting incidents from the row above. For example ($91 − 51) ÷ (94 − 73) = $2.

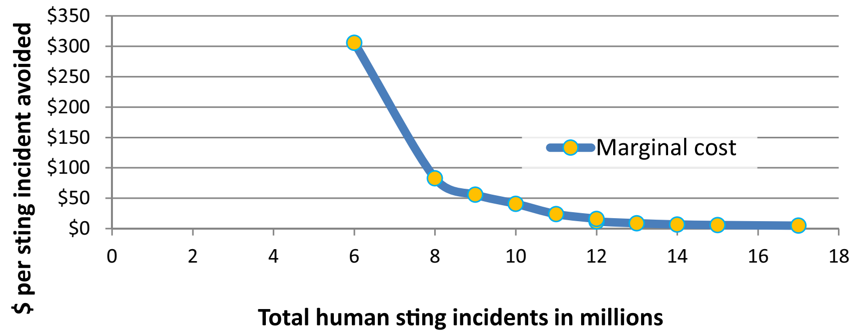

Fig. 5. Marginal cost per avoided human sting incident.

higher costs and larger damages in the longer term. Results indicate that an increase in management effort is economically and socially warranted as the island economy would realize net benefits of $5 billion in total cost savings including a reduction in economic damages of $540 million and avoidance of 2.1 billion human sting incidents over 35 years.

7. Summary

Management effort has a significant impact on Little Fire Ant infestation over time. Under current management, Little Fire Ant infestation will continue to rise in all sectors eventually becoming established in all sectors and in all developed locations on the island in 15 years. By increasing management effort through monitoring, spread prevention, and mitigation, Little Fire Ant spread can be slowed and populations eventually suppressed. Under least cost management, Little Fire Ant infestations are suppressed over the course of 27 years.

Management effort has a significant impact on the number of Little Fire Ant sting incidents. Under current management, people on the island of Hawaii will suffer 2.3 billion sting incidents over 35 years. Their pets will endure 0.9 billion sting incidents over 35 years. With efforts to suppress Little Fire Ant populations, under least cost management during the next 35 years people and pet will suffer fewer sting incidents, down to 94 million for people and 9 million for pets.

Management effort has a significant impact on costs and damages. In the next 35 years the cost of Little Fire Ant under current management will balloon to $6.1 billion. With efforts to suppress Little Fire Ant populations, under least cost management, net costs drop to $51 million, a substantial savings to the local economy.

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