The Hawai`i-Pacific Islands Cooperative Ecosystems Studies Unit &
Pacific Cooperative Studies Unit
UNIVERSITY OF HAWAI`I AT MĀNOA
Dr. David C. Duffy, Unit Leader
Department of Botany
3190 Maile Way, St. John #408
Honolulu, Hawai'i 96822

Technical Report 186

A bioeconomic model of Little Fire Ant *Wasmannia auropunctata* in Hawaii

December 2013

Michael Motoki[1], Donna J. Lee[1,2], Cas Vanderwoude[3,4,5], Stuart T. Nakamoto[6] and PingSun Leung[1]

[1] Department of Natural Resources & Environmental Management, University of Hawaii
[2] DJL Economic Consulting, Honolulu, Hawaii
[3] Hawaii Department of Agriculture
[4] The Hawaii Ant Lab, Hilo, Hawaii
[5] The Pacific Cooperative Studies Unit, University of Hawaii
[6] Department of Human Nutrition, Food & Animal Sciences, University of Hawaii

PCSU is a cooperative program between the University of Hawai`i and U.S. National Park Service, Cooperative Ecological Studies Unit.

Author Contact Information:
Donna J. Lee, DJL Economic Consulting, Honolulu HI, DJL. DonnaJLee@gmail.com. Phone: 808.226-9079

Recommended Citation:
Motoki, M., D.J. Lee, C. Vanderwoude, S.T. Nakamoto and P.S. Leung. 2013. A bioeconomic model of Little Fire Ant Wasmannia auropunctata in Hawaii. Technical Report No. 186. Pacific Cooperative Studies Unit, University of Hawai`i, Honolulu, Hawai`i. 89 pp.

Key words:
Wasmannia auropunctata, bioeconomic modeling, invasive species, socio-economic impacts

Place key words:
Hawaii, Big Island, Kauai, Maui

Editor: David C. Duffy, PCSU Unit Leader (Email: dduffy@hawaii.edu)
Series Editor: Clifford W. Morden, PCSU Deputy Director (Email: cmorden@hawaii.edu)

About this technical report series:

This technical report series began in 1973 with the formation of the Cooperative National Park Resources Studies Unit at the University of Hawai'i at Mānoa. In 2000, it continued under the Pacific Cooperative Studies Unit (PCSU). The series currently is supported by the PCSU and the Hawai'i-Pacific Islands Cooperative Ecosystem Studies Unit (HPI CESU).

The Pacific Cooperative Studies Unit at the University of Hawai'i at Mānoa works to protect cultural and natural biodiversity in the Pacific while encouraging a sustainable economy. PCSU works cooperatively with private, state and federal land management organizations, allowing them to pool and coordinate their efforts to address problems across the landscape.

The Hawaii-Pacific Islands Cooperative Ecosystem Studies Unit is a coalition of governmental agencies, non-governmental organizations and universities that promotes research, education and technical assistance to support better stewardship of imperiled natural and cultural resources within the Pacific.

The HPI CESU is one of 17 cooperative ecosystem studies units across the U.S.

A Bioeconomic Model of Little Fire Ant *Wasmannia auropunctata* in Hawaii

Authors

Michael Motoki[1], Donna J. Lee[1,2], Cas Vanderwoude[3], Stuart T. Nakamoto[4], and PingSun Leung[1]

[1]Department of Natural Resources & Environmental Management, University of Hawaii

[2]DJL Economic Consulting

[3]Hawaii Department of Agriculture

[4]Department of Human Nutrition, Food & Animal Sciences, University of Hawaii

Contact

Donna J. Lee, DJL Economic Consulting, Honolulu HI, DJL.DonnaJLee@gmail.com. 808.226-9079

Abstract

Wasmannia auropunctata, known as the Little Fire Ant (LFA), was first detected on the island of Hawaiʻi (the Big Island) in 1999. It was most probably introduced through imports of contaminated potted plants from mainland USA. We estimate that LFA has now spread to over 4,000 locations on the Big Island and under current management efforts will spread rapidly inundating the Big Island in 15-20 years. Increased efforts in prevention, detections, and mitigation treatments will suppress existing infestations, reduce rate of spread and decrease long term management costs, damages, and human stings. Benefits from increased management are estimated to be $5 billion savings including $540 million in reduced damages and 2.1 billion fewer sting incidents over 35 years.

Keywords: bioeconomic modeling, invasive species, socio-economic impacts

December 2013

Contents

List of Tables

List of Figures

Introduction

Problem statement

Wasmannia auropunctata, 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). LFA will sting endangered reptiles and birds, interfering with reproduction, nesting, and survival of young. LFA will sting cats and dogs in the eyes repeatedly over time and blind them (Theron 2005). Human stings are described as intense and painful with each encounter entailing a dozen or more stings. Human behaviors and habitats allow LFA to move quickly, disperse widely, grow to high densities, and inhabit locations not otherwise possible.

Research purpose

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

Research method

We developed a multi-sector, dynamic, stochastic, bioeconomic simulation model parameterized with government data, original survey data, and information from experts and practitioners. We utilized Microsoft Excel add-in Risk Solver Platform for our analysis.

Roadmap

- LFA problems, mechanisms of spread, history of management
- Model framework, empirical data, management scenarios
- Results, intrepretation, discussion
- Summary, research limitations, future work

Background

Introduced ant species

Humans often introduce non-native plant and animal species to new environments with the aim of enhancing the quality of life (for example the introduction of food plants or animal stock for farming). Some species are introduced because they are visually appealing or for aesthetic reasons. Yet others are accidentally introduced as a consequence of human commerce. In most cases, these newly introduced species are not especially damaging and cause few unwanted impacts. Occasionally, newly introduced species, released from the forces that regulate them in their home environment, multiply rapidly and displace or predate on native species that occupy the same ecological niches (Mack et al. 2000). They can simplify biological diversity, degrade and alter ecosystem functioning, cause economic loss, aesthetic harm and decrease human quality of life (Lowe et al. 2000). These undesirable plants and animals are often referred to as "invasive".

In Hawaiʻi, the arrival of humans increased the rate of establishment of introduced species to the islands (Loope and Mueller-Dombois 1989). The Hawaiian archipelago is especially prone to biological invasions of plants and animals with over 300 serious invasive organisms recorded there out of a total of 5311 non-native plants and animals (Kraus and Duffy 2010).

Although over 15,000 ant species have been described worldwide (Holldobler and Wilson 1990), only a few are considered invasive and have the ability to travel easily with human commerce by hitching rides with cargo, ships and aircraft (McGlynn 1999). Hawaiʻi is one of the few locations worldwide where ants are naturally absent. Prior to human habitation, ants were not a part of the Hawaiian fauna (Loope 1998). Since European settlement however, the islands have been invaded by a progression of invasive ant species, each apparently worse than the preceding species. Currently, at least 45 ant species have been recorded (Krushelnycky et al. 2005). On Maui, the Argentine ant (*Linepithema humile*) has had a significant ecological impact on Haleakala National Park; the eradication effort has been ongoing for 30 years (Krushelnycky et al. 2011).

Distribution

Hawaii's tropical climate is ideally suited for Little Fire Ant establishment and spread.[1] As of 2013, the Little Fire Ant has been recorded on three of the seven main populated islands of Hawaiʻi: Kauai, Maui, and Big Island.

---

[1] Harris, Abbott, & Lester (2012) estimate the range of optimal temperatures for LFA survival to be 65oF to 107oF with temperature being an important factor in spread of the LFA. Disturbed environments, such as forest edges or agricultural fields, provide ideal habitats for the LFA (Ness and Bronstein, 2004 in ISSG, 2009). In Hawaii, 46.9 percent of total land area is zoned for agriculture (Hawaii State Office of Planning, 2006). Hawaii has seen a significant increase in urban population and development in the last few decades (La Croix, 2010). Growing human populations and the corresponding pressures from urban development can exacerbate environmental disruption, and thereby create large areas of suitable habitats for the LFA (Invasive Species Specialist Group, 2009).

Hawaiian Islands

LFA were first detected on the island of Hawaiʻi in 1999 (Conant and Hirayama 2000). Their date of arrival is unknown but was thought to be some years earlier. Subsequent surveys by the Hawaiʻi Department of Agriculture (HDOA) revealed 13 separate infestations in Hilo increasing to 21 known infestations by 2002.[2] By 2004, Little Fire Ant had spread to 31 locations across 76 ha including eight retail and wholesale nurseries (P. Conant unpubl. data; Krushelnycky et al. 2005). Currently, infestations are located mostly along the eastern coast from Kalapana to Laupahoehoe up to an elevation of ~2000ft, scattered populations in the west at Kailua-Kona, South Kona and Kau according the records kept by the Hawaii Ant Lab.[3]

Little Fire Ants were also discovered on Kauai in 2000 on a single property in Kilauea. Efforts to isolate and treat the infestation were undertaken immediately. However some colonies survived and in 2009 had spread to occupy approximately 12 acres. A new eradication program was initiated in 2012, and is still being implemented. Initial results appear promising, but further treatment and extensive monitoring will be needed to confirm success.

In 2008, the Pacific Cooperative Studies Unit conducted a survey of 360 sites on Maui, but no LFA were detected on the island (Starr et al. 2008). Then in 2009, Little Fire Ants were detected on a single property on Maui at Waihe'e infesting an area of 2 acres. A multi-agency effort to isolate, treat and monitor the infestation took 3 years. In 2012, experts declared LFA eradicated on Maui (Vanderwoude et al. 2010).

Known LFA infestations on Kauai, Big Island, and Maui are illustrated in Figure 2, and Figure 3.

---

[2] In 2002 HDOA had detected 11 large and 10 small LFA infestations on the Big Island. Efforts were undertaken to destroy the small infestations and isolate the large ones.

[3] The Hawaii Ant Lab maintains a database of known and confirmed infestations. The Ant Lab also tracks phone calls to their hotline and hits on their online website. We used their data to estimate the current number of infested locations on the Big Island and then used the estimates to establish a baseline for our bioeconomic simulation model. Infested locations are estimated to be 4500 in 2010, 5100 in 2011, 5700 in 2012 and 6400 in 2013.

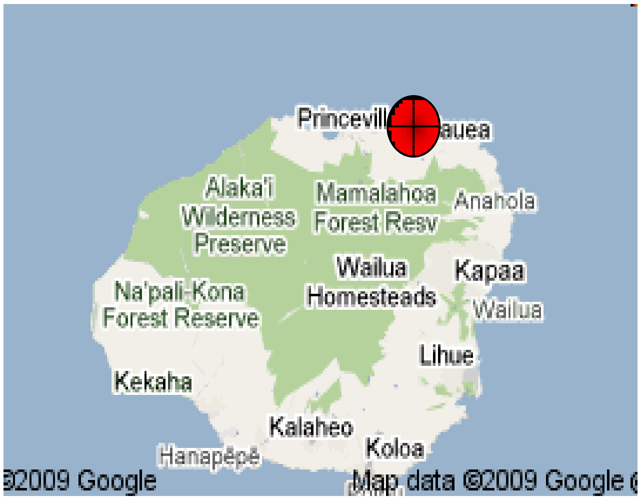


Figure 1 LFA infestation on Kaua‘i

Source: Hawaii Ant Lab

Figure 3 Former LFA infestation on Maui

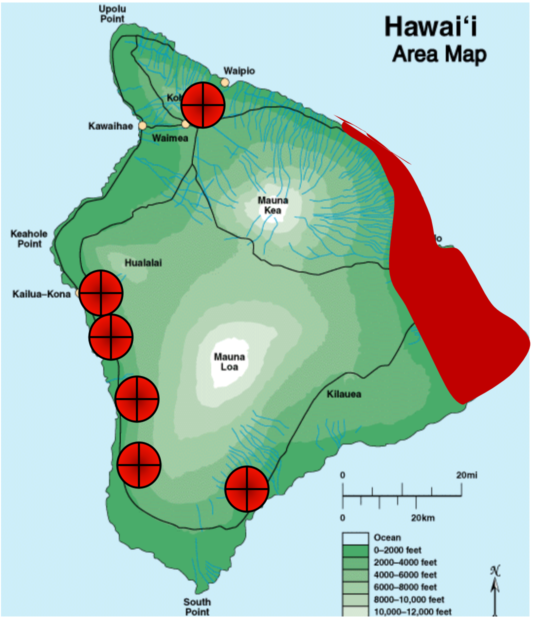


Figure 2 LFA infestation on Big Island

Source: Hawaii Ant Lab

Native range and worldwide distribution

The Little Fire Ant is native to South America and is a common species throughout the lowland regions east of the Andes. Its distribution appears to be limited in its native range by other ant species. However, even there, it can become dominant in disturbed habitats (Wetterer and Porter 2003). The first known record of this species outside its native range was in Gabon (Santschi 1914, cited in (Wetterer and Porter 2003)). In the 100 or so years since, Little Fire Ants have been recorded in Florida (Smith 1929) Galapagos (Lubin 1984), New Caledonia (Fabres and Brown 1978) Solomon Islands (Fasi et al. 2013), Australia, Hawai`i (Conant and Hirayama 2000), Papua New Guinea, Israel (Vonshak et al. 2010), Wallis and Futuna and Vanuatu (Wetterer and Porter 2003). Most recently, this species has been recorded in Guam and the island of Tahiti in French Polynesia (Theron 2005) A map showing the native range of LFA (in orange) and locations where LFA has become established (as black circles) can be seen in Figure 4.

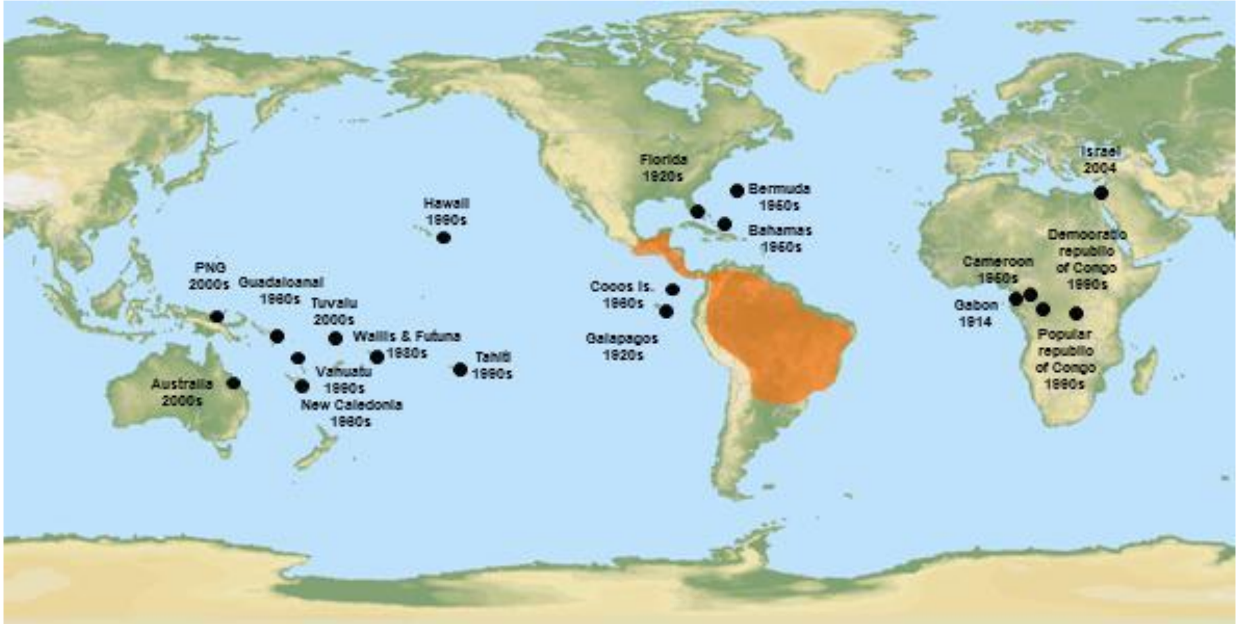


Figure 4 Worldwide distribution of *Wasmannia auropunctata* Little Fire Ant

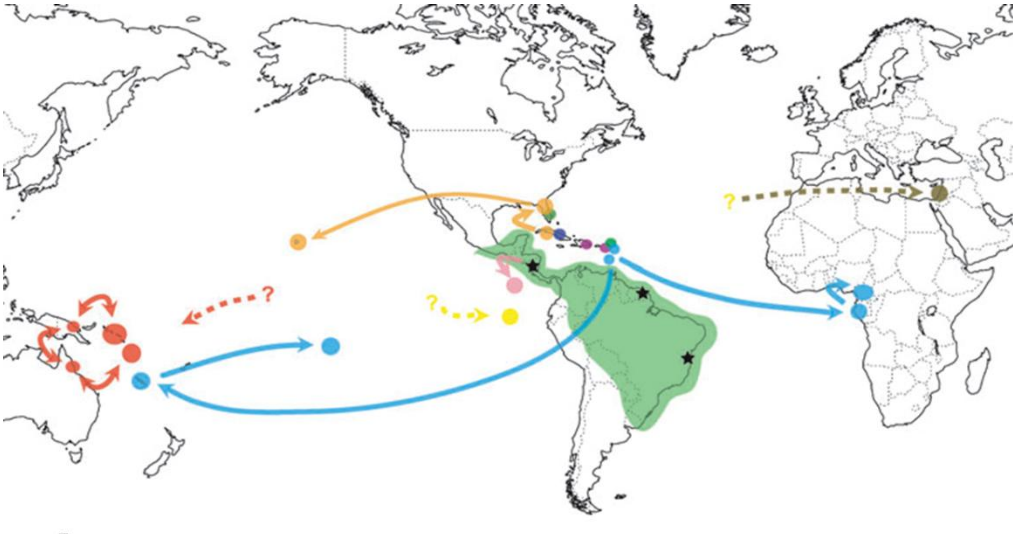
Biology and ecology

Wasmannia auropunctata (Hymenoptera: Formicidae) belong to the sub-family Myrmicinae – a recently evolved sub-family with a generalized ecology (Andersen 1995). This sub-family is characterized by the possession of a distinct post-petiole and a simple gaster and a sting. Little Fire Ants are small, ~1 mm in length and are forest-dwelling (Armbreght 2003). They show a preference for warm, moist and shady environments and workers avoid direct sunlight and dry environments. Colonies are small, numerous and can be found in the ground layer, in vegetation and the canopies of trees. Little Fire Ants utilize any available niche for nesting sites: leaf litter, under rocks or stones, cracks and crevices in trees, hollows in decaying organic material etc. Colonies will readily relocate when their current nest location becomes unsuitable or a better location becomes available.

Reproduction

Little Fire Ants possess an unusual reproductive biology. Normally, when queens reproduce, their offspring share both paternal and maternal DNA. However, for Little Fire Ants, this is not always the case. Daughters of a queen only possess maternal DNA and are essentially clones of their mother. Similarly, males do not possess any maternal genetic material. Arguably, the males and females are two distinct species. Some genetic mixing does occur; however for invasive populations, clonal reproduction is the norm. A detailed explanation of this very unusual form of reproduction is beyond the scope of this report but is available elsewhere (Fournier et al. 2005, Foucaud et al. 2007 and Foucaud et al. 2010).

Clonality in this species has allowed geneticists to analyze the likely sources and pathways of invasive populations worldwide by tracing clonal lines present in invaded sites (Foucaud et al. 2010). In the Pacific region, five separate clonal lines have been identified, suggesting there were five separate introductions to the region, shown in Figure 5 where the colors represent common clonal lines and presumed introduction pathways.



From:

Foucaud, J. Orivel, J. Loiseau, A. Delabie, J.H.C. Jourdan, H. Konghouleux, D. Vonshak, M. Tindo, M. Mercier, J. Fresneau, D. Mikissa, J. McGlynn, T. Mikheyev, A.S. Oettler, J. and Estoup, A. (2010). Worldwide invasion by the little fire ant: routes of introduction and eco-evolutionary pathways. *Evolutionary Applications*. 1-13

Figure 5 Worldwide clonal lines of *Wasmannia auropunctata*, Little Fire Ant

Different populations with the same clonal lines are very likely to be linked and share common introduction pathways. The clonal forms found in Hawai‘i and Florida USA are identical but distinctly different from other populations in the Pacific region.

Density

Introduced Little Fire Ant populations can achieve extraordinary population densities – far greater than the species they displace. In Hawai`i’s tropical orchards, LFA populations average 20,000 individuals per square meter (Souza et al. 2008). Queen density is also high. Using empirical data for worker to queen ratios elsewhere (Ulloa-Chacon and Cherix 1990) queen density in Hawai‘i are estimated to be between 36 and 77 per square meter. This level of queen redundancy confounds efforts to control the species.

Invasive traits

In common with other invasive ant species (Passera 1994), Little Fire Ants exhibit several traits that together bestow them with the potential for invasiveness: Polygyny (more than one queen per colony); polydomy and unicoloniality (multiple nest sites which are inter-connected); high inter-specific aggression (aggressive defense of territory and resources against competing species); relocation via human commerce (an ability to travel to new locations attached to cargo and people); and formation of mutualistic relationships (protecting other insects in return for food).

Polygyny

A typical ant colony consists of a single reproductive queen attended by many sterile worker ants. In a mature colony, new queens and males are produced at times when conditions for colony founding are optimal. The new queens and males fly from the nest in synchrony, mate while in flight, and the newly mated queens return to the ground, each attempting to form their own independent colony. The role of males ceases at this time and they do not return to the parental nest.

However, nests of many invasive ant species (including Little Fire Ants) contain many queens, and workers do not appear to distinguish between them or attempt to assassinate surplus queens. This feature gives the species two competitive advantages. First, with most ants the founding phase of a new colony carries a high risk of failure. A newly mated queen needs to lay an initial clutch of eggs and care for them until the larvae reach adulthood, before focusing exclusively on egg-laying. New queens often suffer from predation or fail to raise sufficient workers to form a colony. For Little Fire Ants and many other invasive ant species however, newly mated queens simply re-enter the parental colony, or move a short distance with existing workers to found a new satellite colony that remains in contact with the parental one

The second advantage of polygyny is that the task of egg laying is shared between multiple queens. In single queen colonies, the death of the queen results in the end of the colony. Worker ants have a short life cycle and as they die, they are not replaced by new workers. However, in multiple queen colonies, the death of one or more queens has no lasting effect on egg production. Remaining queens simply increase their rate of egg laying to compensate. Many control methods focus on killing the queen for success and when colonies possess multiple queens, all must be eliminated.

Polydomy and unicoloniality

Ant colonies, even from the same species, are highly competitive and expend great resources to defend their territory and resources from other colonies. Large amounts of energy may be expended in this activity. Almost all invasive ants share the traits of polydomy and unicoloniality which dramatically reduces their cost maintaining territory.

Individual Little Fire Ant colonies do not compete with each other. Instead they form an inter-connected network of nodes or buds. They work cooperatively, share food, workers, brood and queens and jointly defend their combined foraging areas against competing ant species. Territorial defense is only needed at the outer edges rather than around each individual colony and the ratio between border length and foraging area reduced substantially. The surplus energy resulting from this strategy is re-allocated to colony expansion and is one key to their invasive ability.

Inter-species aggression

In contrast to the high level of within-species cooperation, Little Fire Ants aggressively defend their combined foraging territory from competing ant species and other animals that might deplete available resources. Any competing ant that wanders within the defended area is overcome by sheer weight of numbers. Thus it is rare to find colonies of other ant species within areas infested by Little Fire Ants.

Dispersal ability

An invasive organism needs a means to relocate to new environments. Little Fire Ants do not disperse by flight, but a colony fragment of a few workers and one reproductive queen is all that is needed to establish at a new location. A viable colony fragment is able to fit comfortably into an area smaller than a match-box and is therefore easily hidden within cargo, baggage, building materials, automobiles, potted plants, produce or other items. Increasing rates and volumes of human commerce provide the vector needed for Little Fire Ants to move from location to location.

Mutualisms

Another factor contributing to the success of *Wasmannia auropunctata* as an invader is an ability to capture and redirect resources in their environment. One method this species utilizes is through the formation of mutualistic relationships with Homoptera (scales, mealybugs and other plant pests) (Way 1962; Helms and Vinson 2002). Little Fire Ants “farm” these animals, protect them from natural predators and consume the sugary exudates the insects produce. Of all invasive ant species, Little Fire Ants appear to be one of the most effective at forming and exploiting these relationships.

This “farming” of Homopterans rewards the ant colony with additional resources not previously available in the environment, allowing colonies to grow and spread. Homopteran density becomes greater because the ants protect them from natural predators, resulting in availability of even more resources. The mutualistic relationships Little Fire Ants exploit are one reason their population densities are higher than the ants they displace.

Impacts

In Hawaii, the relationships between human habitation, agriculture and the environment are spatially close. Dwellings and urban structures are often in immediate proximity to the natural environment and agricultural areas. Little Fire Ants profoundly affect each of these sectors.

LFA are a serious pest of dwellings and urban structures (Fabres and Brown 1978, Delabie 1995) and are very difficult to exclude. They infest houses, foraging throughout homes, stinging people, children and domestic animals. The stings affect people to varying degrees from causing a painful rash to extreme reactions resulting in large raised welts. In external areas around dwellings, they will nest in vegetation and on the ground. However, they are easily dislodged from their arboreal locations, falling on unsuspecting people and domestic animals. Here, they can become trapped in clothes or in animal fur. At this time, Little Fire Ants emit an alarm pheromone which will cause all nearby ants to sting in unison.

In areas infested with Little Fire Ants, it is common to observe domestic animals with clouded corneas. This condition is known as tropical keratopathy or Florida spots and is thought to be caused by entry and growth of mycobacteria within the corneal layers after a physical injury to the eye (Gelatt, 1999). Although not exclusively due to Little Fire Ants, there is much anecdotal evidence that their stings cause this condition. This has recently been confirmed by an epidemiological study in Tahiti (Theron 2005).

Little Fire Ants displace other ant species and prey on insects and vertebrates in both natural and human-modified environments. Often other animals sharing the same habitat simply relocate to avoid the discomfort of being constantly stung. Although there are few studies of the total ecological impacts caused by this species, there are many reports describing their impacts on individual species or species groups (Clark et al. 1982, Lubin 1984, Jourdan 1997, Wetterer et al. 1999, Armbreght 2003, Le Breton et al. 2003, Walker 2006, Ndoutoume-Ndong and Mikissa 2007, Beavan et al. 2008, Vonshak et al. 2010).

Agricultural systems are impacted in three main ways by the presence of Little Fire Ants. First, the mutualism between homopterans and ants causes population explosions of these plant pests (Spencer 1941, Delabie 1988, 1990, Delabie and Cazorla 1991, de Souza et al. 1998, Souza et al. 2008, Fasi et al. 2012). This decreases plant health and productivity declines. Second, Little Fire Ants sting agricultural workers, making daily management and harvesting tasks much more difficult. Third, workers quit their jobs rather than enter infested locations (Fabres and Brown 1978).

Eradication

Successful cases of LFA eradication are documented for Marchena island in the Galapagos (Causton et al. 2005) and on Maui (Vanderwoude et al. 2010). Details appear in Box 1

Box 1. Case Study: Eradication of LFA in Maui

In October 2009, a Maui farmer in Waihe'e reported a suspicious ant. The Hawaiʻi Ant Lab confirmed that it was Little Fire Ant (LFA). The Hawai`i Department of Agriculture (HDOA) coordinated a rapid response, first surveying the area to ascertain the extent of the infestation. After determining that the infestation was isolated, agencies responded quickly to contain and treat the infestation.

The Hawaiʻi Department of Agriculture Pesticides Branch issued a permit allowing use of a paste bait to be sprayed into trees to destroy the colonies nesting above ground.

The Hawaiʻi Ant Lab (University of Hawaii Pacific Cooperative Studies Unit) provided expertise in ant identification, treatment regime and training as well as developing an eradication plan. A multi-agency taskforce was formed to coordinate the response. Hawaiʻi Department of Agriculture and the Maui Invasive Species Committee (MISC) provided the human resources needed to survey the area, developed and delivered the outreach strategy to secure public support and cooperation. The County of Maui also supported the response.

Treatments continued monthly for one year. After treatments ceased, monitoring continued for 18 months, and in 2012 LFA at the Waihe'e farm was declared eradicated. Early detection, rapid response, persistent follow-up, arboreal paste bait, public awareness, and inter agency cooperation are credited for the success

Source: Press Release: Stinging Ants Appear Eradicated on Maui, NR10-13 - October 21, 2010

Box 2. Case Study: Eradication of LFA in the Galapagos

In 2001, an effort was made to eradicate Little Fire Ants from 21 hectares on Marchena Island in the Galápagos Archipelago (Causton et al. 2005). Amdro® (a bait containing hydramethylnon) was applied at three-month intervals over a period of 9 months. Sites were monitored for LFA using bait stations.

Findings After the first Amdro® application, 700 of the 33,639 bait stations showed no signs of LFA. After the second Amdro® application 11,058 bait stations were LFA free. After the third application, all but three bait stations were LFA-free. The total cost including personnel, preparation, field trips, lab work, and overhead was $212,736 or $13,680 per hectare.

LFA management on the Big Island

Historical management

The first detection of Little Fire Ants on the island of Hawaiʻi was in March 1999. Ant specimens from a retail nursery were collected by Hawaiʻi Department of Agriculture staff and later positively identified by entomologist Dr. Neil Reimer. This species had almost certainly been present in Hawai‘i for some years prior to its detection. The Hawaii Department of Agriculture, as lead response agency, attempted to contain and eradicate the known infestations. HDOA entomologist Pat Conant led the response effort to quarantine interisland movement of nursery products, and attempted to eradicate small LFA populations and to contain larger LFA populations. There appeared to be a number of obstacles to initial attempts at eradicating this new species. The possible source of the infestation had been identified as a commercial potted palm nursery; however the State was unable to gain access to records indicating where the palms had been sold. This allowed new infestations more time to become established before being detected. At the time, the public was unaware of the pest and its potential impacts. This resulted in a general apathy to the issue. Island-wide support may have aided efforts through early detection of new infestations. The State had resources to treat LFA on both public and private land but was not always able to gain access to infestations on private land. No effective treatment pesticides were available for fruit trees and vegetable crops which meant not all infestations could be controlled. Additionally, there was no method for effectively applying ant control products to trees. These untreated arboreal nests that survived treatments simply recolonized the ground layer after treatments ceased. Some infestations were in areas with heavy vegetation and steep terrain. These were virtually impossible to treat.

By 2003 it became evident that eradication efforts were not successful. Little Fire Ants continued to spread and the HDOA shifted to a strategy to manage impacts and provide advice to affected people and industries. Some treatments continued, especially at sensitive sites such as schools and public use areas. As the pest spread and impacts became more severe, calls for more effort to manage these impacts increased. This included a resolution by the county of Hawai‘i (resolution 816-08) that called for the creation of a position to coordinate mitigation efforts, formation of a taskforce and additional public outreach and education.

Current management

In late 2008 an invasive ant specialist position was created and funded through the Hawaii Invasive Species Council. This position has evolved to become the Hawai‘i Ant Lab with a staff of three. The lab is located in Hilo Hawai‘i and provides outreach, education, training, advice and mitigation efforts for all invasive ant issues in the state of Hawai‘i. The management strategy includes a website[4] that contains substantial resources on impacts and remedies for affected people and industries. Current management of LFA on the Big Island involves a multi-pronged approach that includes the activities of the Hawai‘i Ant Lab (identification, eradication, advice,

---

[4] www.littlefireants.com

training and outreach) and the Big Island Invasive Species Committee who provide substantial outreach as a part of their general invasive species outreach efforts. The five island Invasive Species Committees in Hawai‘i (Maui, Oahu, Hawai‘i, Kaua‘i and Moloka‘i) each have an ongoing program to educate and engage the public regarding the risks LFA poses to each island. Education on the Big Island includes giving talks at schools and group functions, conducting surveys, holding workshops, and setting up displays at special events. Engagement includes public involvement in reporting new infestations, participating in control efforts, and preventing spread. The Hawaii Department of Agriculture (HDOA) Plant Industry Division enforces the state of Hawaii's strict invasive species policies which require testing of agricultural products, animals, and potted plants for LFA (http://hdoa.hawaii.gov/pi/). Cut flowers and foliage however can be shipped without testing.

Monitoring and detection

Early detection of Little Fire Ants significantly improves the probability that the infestation can be eradicated at a low cost. Monitoring for Little Fire Ants involves placing chopsticks or coffee stirrers baited with peanut butter, and retrieving these about an hour later to see if any ants have congregated.

Although the monitoring procedure is relatively simple, the ants collected as a result require expert identification to determine their species identity. There are at least four other ant species that superficially resemble Little Fire Ants and determination requires the use of a high-powered microscope with at least 40x magnification. Also, this species resides in shaded areas - in plant crevices, in trees and beneath leaf litter. The foraging area of individual colonies is small, so high bait density is needed to adequately survey an area.

Mitigation treatment[5]

There are currently no candidates for biological control of this species, and it is unlikely one will become available in the short-medium term. Several conventional strategies can be employed to control or mitigate existing Little Fire Ant populations, including use of broad spectrum contact or residual pesticides, toxic baits and treatment of infested commodities by irradiation or heat (Hara et al. 2011).

---

[5] Mitigation treatments reduce the size of an invasion using chemical applications, biological controls, mechanical removal, manual extraction, or other means (Olson, 2006).

Contact pesticides such as carbaryl have little residual effect. Sprays need to reach all the ants including those that remain behind in the colony. Generally, contact sprays are best suited to treatment of produce and other commodities, potted plants and the associated potting medium.

Residual pesticides, once applied, remain active in the environment for weeks or months; any insect that comes into contact with treated materials (the ground, structures etc.) will be affected by the pesticide and eventually die. This type of pesticide is ideal for forming a "chemical barrier" to exclude Little Fire Ants from entering a home or other structure. They are also used to treat the ground and non food-bearing plants. Many synthetic pyrethroids (such as bifenthrin) are labeled for this purpose.

Toxic baits have significant advantages over broadcast applications of persistent pesticides (Williams et al. 2001) including lower overall pesticide use and reduced non-target impacts (Williams 1983). They utilize ant social behaviors of foraging, recruitment and stomodeal trophallaxis to direct toxicants to nestmates, and most importantly, the queen or queens of the colony. Exploiting the natural behaviors of ants is an efficient management strategy that potentially lowers pesticide and labor costs (Williams 1983, Klotz et al. 2003, Tollerup et al. 2004).

An effective bait formulation is comprised of an attractant (the bait matrix), a toxicant (the active ingredient) and a carrier to facilitate application. Candidate toxicants undergo rigorous testing and must demonstrate specific properties including delayed mortality, non-repellency at high concentrations, and efficacy when diluted by trophallaxis (Williams 1983, Braness 2002, Tollerup et al. 2004, Rust et al 2000). Few active ingredients exhibit all of the necessary traits (Levy et al. 1973, Williams 1983).

A staggering variety of proprietary bait formulations are available on the market. However, most are very similar. Often, they are based on a matrix of defatted corn grit impregnated with soya oil and small amounts of a toxicant. Some of the common toxicants are hydramethylnon, indoxacarb, fipronil, methoprene and pyriproxyfen.

Habitat management

Non-chemical mitigation practices should also be considered. Clear cutting vegetation and eliminating leaf litter can serve to reduce the amount of nesting habitats that LFA prefer, thus reducing nest density. Another option open to some residents is that of "xeriscaping" or the use of drought tolerant plants in landscapes around homes. Reduced irrigation and the creation of a drier microclimate will result in a landscape inhospitable to Little Fire Ants. This option is not readily available for residents of east Hawai‘i which experiences extremely high annual rainfall.

Previous work

Modeling ant growth and dispersal

Modeling growth

Logistic equations can be used to estimate population growth over discrete time periods. When invasive species have a definite carrying capacity, the logistic growth equation is sometimes used to model growth and dispersal of invasive species (e.g. Leung et al, 2002; Burnett et al, 2007; Eiswerth & Van Kooten, 2007). The logistic growth equation is given by, $\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right)$, where t represents time, N is the population size, the constant r is the intrinsic growth rate, and K is the carrying capacity.

Modeling short distance dispersal

When dispersal via colony budding is small, a simple exponential equation can be used to model short distance dispersal. Several studies use reaction-diffusion to model dispersal of an invasive species (e.g., Carrasco, Baker, MacLeod, Knight, & Mumford, 2010; Leung, Lodge, Finnoff, Shogren, Lewis, & Lamberti, 2002; Burnett, Kaiser, & Roumasset, 2007). Reaction-diffusion models use partial differential equations to incorporate dynamic and spatial characteristics of competing species (Holmes, Lewis, Banks, & Veit, 1994). For invasive species applications, Holmes, Lewis, Banks, & Veit (1994) describe reaction-diffusion, a continuous non-stochastic process for predicting short-range dispersal.

Modeling long distance dispersal

When carrying capacity and distance are not limited, a more complex formulation is required. The invasion pattern of the Argentine ant[6] *Linepithema humile*, and other tramp ant species is human mediated (Suarez, Holway, & Case, 2001; Souza, Follett, Price, & Stacy, 2008). The incidence of long distance dispersal are irregular and stochastic (Wilson, Dormontt, Prentis, Lowe, & Richardson, 2009). Gravity models can be used to quantify human-mediated long distance dispersal of invasive species (e.g., Nathan, Perry, Cronin, Strand, & Cain, 2003) using commerce or traffic flows as a proxy for long distance invasion pathways (e.g., Hastings, et al., 2005; Bossenbroek, Kraft, & Nekola, 2001). Diffusion type models (Carrasco, Baker, MacLeod,

---

[6] Similar to the LFA, the Argentine ant is a tramp ant that disperses by humans and colony budding.

Knight, & Mumford, 2010) assume dispersal occurs as a result of individuals emanating outwardly though a random walk.

Several authors (e.g., Eiswerth & Van Kooten, 2007; Kot & Schaffer, 1986; Hastings, et al., 2005; Law, Murrell, & Dieckmann, 2003) modeled dispersal using a probabilistic transition function[7] which takes the form of a dispersal kernel but unlike the diffusion models comprised of partial differential equations, dispersal kernels do not always have a closed-form solution.

Scanlan and Vanderwoude (2009) used stochastic cellular automata to model human-mediated long distance dispersal of red imported fire ant (*Solenopsis invicta* Buren) within locations of size 100 km by 100 km and to new locations. The model included 200 cells over 4 million square km in Australia with each cell equally likely to become infested with RIFA. The model was run over a 40 year period from 1996 to 2035.

Modeling invasive species management

Types of models

Early management models were static and assumed perfect knowledge. Later models were dynamic (Eiswerth & Johnson, 2002; Eiswerth & Van Kooten, 2007) and allowed for uncertainty (e.g., weather, temperature, human travel patterns). More recent research includes stochastic elements.

In the "economic threshold" model, the density of the invasive species population determines the level and timing of management. The economic threshold is defined as the density of pest population where the benefit of treatment just exceeds its cost (Mumford & Norton, 1984). Economic threshold models include uncertainty using a Bayesian decision theory approach which requires that individuals have previous knowledge about parameter inputs.

Optimal control models use diffusion-reaction equations to represent spread to generate closed-form solutions (e.g., Burnett, Kaiser, & Roumasset, 2007; Carrasco, Baker, MacLeod, Knight, & Mumford, 2010; Mehta, Haight, Homans, Polasky, & Venette, 2007; Taylor & Hastings, 2004; Olson & Roy, 2003). Optimal control is appropriate for continuous state dispersal.

For discrete state dispersal, dynamic optimization models have been applied (Leung et al. 2002).

---

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

Types of management

Management activities include prevention, detection, and mitigation.

Prevention is especially important when invasive species are spread through human mediated travel. Prevention activities include monitoring invasion pathways associated with trade, transport and travel and inspecting potential vectors (Perrings, 2005). Preventing introduction allows damages to be avoided all together (Leung et al. 2002). Where introduction is treated as a random variable, prevention can be modeled as a reduction in the probability that an invasive species is introduced (Olson, 2006). Leung et al. (2002) model prevention success with an exponential distribution that exhibits diminishing marginal returns with respect to the level of prevention effort.

Mehta et al. (2007) stipulate that investment in prevention measures may not be desirable when the number of invasion pathways is large or when the probability of introduction is small. Alternatively, detection involves locating and identifying invasive species so that appropriate mitigation actions can be taken. Mehta et al. (2007) model detection success as exponentially distributed, $q(\tau|S,k) = kSe^{-kS\tau}$, where the probability of detection (q) at time τ increases with detection effort (S) and an efficacy parameter (k). Detection effort is measured in man-hours spent on searching for the invasive species, the efficacy parameter can be modeled either as a deterministic constant or uncertain variable. Mehta et al. (2007) acknowledge the importance of prevention and they recommend that future studies incorporate all three approaches to management. Mehta et al. (2007) also recommends incorporating a more realistic model of spatiality. Carrasco et al. (2010) also investigate an optimal control approach to managing invasive species that utilizes control and detection, but instead focus on reducing the velocity (i.e., rate of spread) rather than reducing the size of the invasion.

Mitigation treatment usually involves chemical, mechanical, manual, or other means to reduce the size of an invasion (Olson, 2006). The effectiveness of treatment can be represented by the proportion of the invasive species population killed per treatment. Lichtenberg & Zilberman (1986, p. 263) define mitigation (alternative names include control, abatement, or kill) functions as “the proportion of the destructive capacity of the damaging agent eliminated by the application of a level of control agent X” and stipulate that this function has the properties of a cumulative probability distribution. Feder (1979) stipulates the function that describes the effectiveness of mitigation k(x) should exhibits decreasing returns to scale with respect to the amount of mitigation x (e.g., applications of pesticides, hours of physical removal). The effectiveness of mitigation can also be a stochastic process since it is affected by environmental factors such as weather, temperature, and wind (Feder, 1979). In addition, unlike traditional factors of production, damage control agents may impede productivity (e.g., through environmental degradation, or harmful effects on humans) rather than enhance it (Lichtenberg & Zilberman, 1986).

There is an extensive econometric literature on modeling mitigation methods (e.g., Carpentier & Weaver, 1997; Blackwell & Pagoulatos, 1992; Babcock, Lichtenberg, & Zilbe, 1992; Carrasco-Tauber & Moffitt, 1992; Saha, Shumway, & Havenner, 1997; Lichtenberg & Zilberman, 1986) where an exponential mitigation function is discussed. Taylor & Hastings (2004) model mitigation actions in discrete categories show rising levels of investment in mitigation. Olson and Roy (2003) use dynamic programming to characterize the conditions under which eradication, mitigation, and no mitigation are optimal. In addition to characterizing the mitigation function in a dynamic optimization framework, they also find that "the marginal costs of [mitigation] are more sensitive to changes in the invasion size than to changes in [mitigation treatment]" (cited in Olson, 2006).

Cost of management

Modeling marginal cost of management as a linear function assumes marginal costs are proportional to the size of the infestation managed (Hastings, Hall, & Taylor, 2006; Burnett, Kaiser, & Roumasset, 2007). Olson (2006) asserts that management cost functions and damage functions should be convex. Managers work within an annual budget. However, including a budget constraint will restrict the solution space and could yield more costly results. Taylor & Hastings (2004) use an annual budget constraint as the primary limiting factor when parameterizing their optimization model. Their model's objective is to minimize the infestation, and the upper bound on their decision space (i.e., the set of management decisions) is determined by the annual budget constraint. Hastings, Hall, & Taylor (2006) find that results are highly sensitive to annual budget.

Modeling invasive species impact

Linear damage functions assume a constant marginal damage (Gutrich et al 2007). Olson (2006) states that nonlinear damage functions more accurately reflect damages (e.g., pest damage to agricultural crops), i.e. higher marginal damages with larger infestations (Haight & Polasky, 2010). Burnett, Kaiser, & Roumasset (2007) specify a quadratic damage function.

LFA Bioeconomic Model

Model overview

We simulate LFA dispersal over time with an aggregate bioeconomic model comprising three sub-models: impact, biological, and management.[8 9] The phases of infestation, impact, and management are illustrated by the conceptual diagram shown in Figure 6. The aggregate model is run as a non-linear optimization with the objective of minimizing LFA impacts. Infestation is simulated with the biological submodel. Control activities occur within the management submodel.

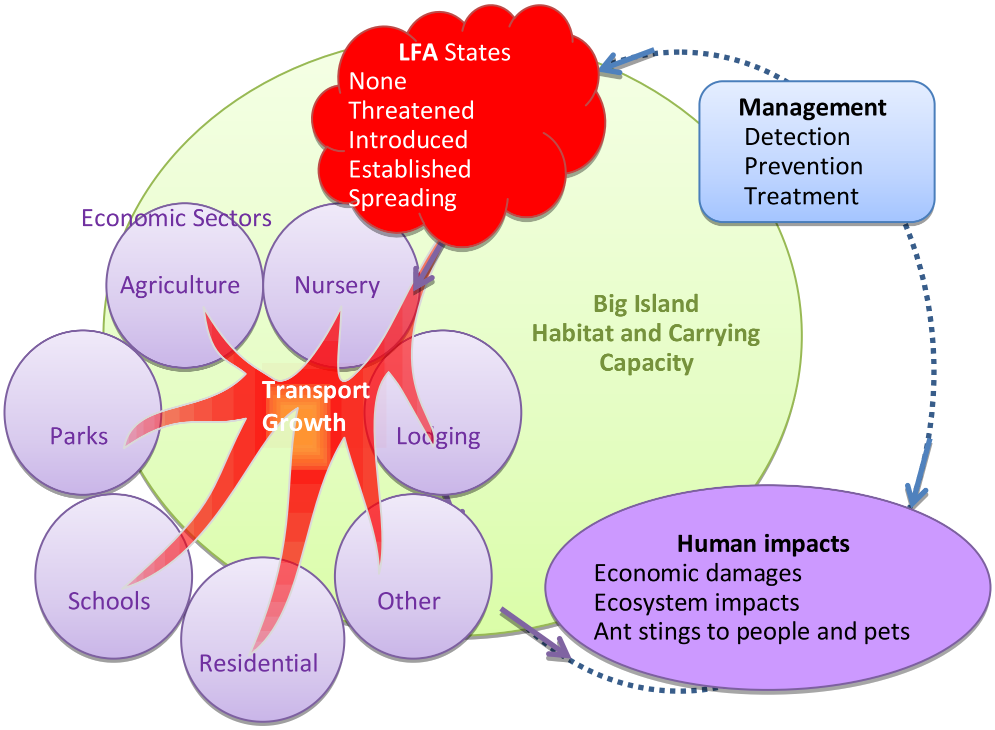


Figure 6 Conceptual diagram of LFA Bioeconomic Model

The <u>management</u> sub-model quantifies the effect of management decisions on LFA growth and dispersal. Management activities include <u>prevention</u>, <u>detection</u>, and <u>mitigation treatment</u>. Prevention reduces the likelihood of LFA leaving an infested area via long-distance jump

---

[8] Leung, et al. (2002) specified a framework for modeling invasive species using three components: abundance and spread, economics, and transport and establishment and assert, “each step in this invasion process is probabilistic.” They applied the model to a case of introduction of zebra mussels to a U.S. lake.

[9] The framework is consistent with the invasion model put forth by Heger & Trepl (2003).

pathways. Detection allows new infestations to be treated before they become established. Mitigation treatments reduce the extent of infestation measured in number of infested areas.

The LFA biological sub-model includes four phases: transport, introduction, establishment, and growth. The transport phase involves LFA propagules leaving one site and traveling to another. The introduction phase determines at each new site the portion of transported propagules that form colonies. Initially the new colonies go unnoticed (and unmanaged) unless detection activities are employed. If new colonies are detected, they can be more easily eradicated. If undetected and unmanaged, new colonies can establish. Once established, LFA begin multiplying, cause more widespread damage, and become more difficult to eradicate. In the growth phase, LFA can disperse propagules to new sites.

The LFA impact sub-model quantifies economic (e.g., economic losses, management costs) and social damages (e.g., the number of LFA stings) based on sector and extent of the infestation. Economic losses are sector dependent and vary with the size and extent of the infestation. Management costs are based on management effort, the cost of labor and materials, using best management practices and current technology. Sting incidents are based on number of infested sites in each sector; human population, demographics, and employment in each sector. A sting "incident" may involve multiple LFA stings.

Model scope

For general modeling purposes, we specified n discrete economic sectors that are susceptible to an LFA invasion, with index $i = 1, \cdots, n$. All infestation occurs within these n sectors. We identified six economic sectors susceptible to LFA impacts and included an additional seventh sector to account for spread into all other areas, $n = 7$. A detailed overview of the seven sectors included in this research appears in the empirical data subsection.

We model the spread, damages, and costs of the Big Island LFA invasion over a 35-year period. The 35-year time horizon was sufficiently long to achieve a steady state across all management scenarios.

Management submodel

The management submodel describes and incorporates the effects of management on the LFA invasion process. It defines three management activities: prevention, detection, and mitigation treatment. In particular, it models how management decisions affect LFA growth and transport (in the biological submodel). We assume best management practices are followed. Prevention and monitoring effort is measured in units of person-hours per sector per year, while mitigation treatment is measured in the number of insecticide applications.

We assume the success of management activities follows a Bernoulli process. In the mitigation treatment case, for example, we assume the probability of successfully eradicating a single infestation p is constant for every application of insecticide, and therefore follows a geometric distribution. We define the probability of successfully killing an infestation at any one time t using the cumulative distribution function of the geometric distribution

$$\theta = 1 - (1 - p)^n \tag{1}$$

Where n is the number of trials, which for mitigation treatment is the number of applications. Thus, as the number of applications n increase, probability of killing the infestation increases and is brought closer to one. Since the efficiency and cost of management actions were not known with certainty, a sensitivity analysis was conducted to investigate how outcomes change as these parameters were varied. These sensitivity parameters are discussed in the results section.

Prevention

Prevention encompasses efforts to thwart new infestations by reducing movement of LFA from one site to another. The effectiveness of prevention efforts $\theta_{i,t}^{prevent}$ depends on the probability of stopping spread $\lambda_i^{prevent}$ and level of prevention effort, $d_{i,t}^{prevent}$:

$$\theta_{i,t}^{prevent} = 1 - \left(1 - \lambda_i^{prevent}\right)^{d_{i,t}^{prevent}} \tag{2}$$

Here $d^{prevent} \in [0, \infty)$ is the decision variable for prevention expenditures in units man-hours per year. When $d^{prevent} = 0$ prevention is non-existent, and $\lim_{d^{prevent} \to \infty}\left(\theta_{i,t}^{prevent}\right) = 1$.

Detection

LFA monitoring and surveillance increase the likelihood that new infestations are identified early so they can be destroyed before they can establish, grow, and spread. Detection effectiveness θ_i^{detect} depends on the probability of detecting an LFA infestation λ^{detect} and level of detection effort $d_{i,t}^{detect}$ [10] :

---

[10] This formulation of early detection is a modification of the function form proposed by Carrasco, et al. (2010).

$$\theta_{i,t}^{detect} = 1 - \left(1 - \lambda_i^{detect}\right)^{d_{i,t}^{detect}} \quad (3)$$

The detection decision variable $d_{i,t}^{detect}$ is measured in number of man-hours invested in each sector per year.

Mitigation

Mitigation effort reduces LFA population at infested sites. Here mitigation effort is measured in terms of the number of insecticide applications $d_{i,t}^{mitigate}$ up to a maximum of four times per year. Each insecticide application destroys the LFA population with probability $\lambda_i^{mitigate}$ such that the probability of eradicating LFA $\theta^{mitigate}$ increases with mitigation effort $d^{mitigate}$

$$\theta_{i,t}^{mitigate} = 1 - \left(1 - \lambda_i^{mitigate}\right)^{d_{i,t}^{mitigate}} \quad (4)$$

Biological submodel

The biological submodel simulates the growth, spread, and dispersal of LFA over time and hence determines the level of infestation in each sector $N_{\mathrm{i,t}}^{(\dots)}$, the superscript in parentheses denotes biological phase: introduced, incubated, established; for sector i and time period t; the number infested sites in each sector is an integer greater than or equal to zero $N_{\mathrm{i,t}}^{(\dots)} \geq 0$.

Starting infestation

Initially, the starting infestation $N_{i,0}^{start}$ is equal to $N_i^{initial}$ an exogenous parameter.

Growth

LFA reproduce and spread within an economic sector. Growth occurs at rate λ^{growth} [11] such that $N_{i,t}^{growth}$ is the number of newly infested sites each year:

---

[11] λ is assumed constant over time. The kernel is constant so there no temporal variability in spatial spread. New propagules can spread to infested as well as uninfested sites. Competition, predation, and mutualism assumed are constant and embodied in the intrinsic growth rate. The impact of weather on growth is also assumed constant.

$$N_{i,t}^{growth} = \lambda^{growth} \cdot N_{i,t}^{pregrowth}\left(1 - \frac{N_{i,t}^{pregrowth}}{N_i^{max}}\right) \quad (5)$$

Here $N_{i,t}^{pregrowth}$ includes sites with an established infestation $N_{i,t}^{establish}$ and all the incubating sites (i.e., $N_{i,t}^{pregrowth} = N_{i,t}^{establish} + \sum_{w=0}^{3} N_{i,t,w}^{incubate}$). Within a sector, the number of newly infested sites increases over time logistically[12] up to the sector's carrying capacity N_i^{max}.

Transport

The number of sites $N_{i,t}^{out}$ capapble of spreading LFA to other sites is the number of infested sites $N_{i,0}^{start}$ times $\lambda_i^{invasion}$ the probability of producing LFA propagules[13] and $\left(1 - \theta_{i,t}^{prevent}\right)$ the proportion of sites from which spread is not prevented:

$$N_{i,t}^{out} = \lambda_i^{invasion} N_{i,t}^{start}\left(1 - \theta_{i,t}^{prevent}\right) \quad (6)$$

Dispersal is determined by the transport matrix (dispersal kernel) k where where $\sum_j^n k_{j,i} = 1$. The proportion of sites that are uninfested at time t is $\left(\frac{N_i^{max} - N_{i,t}^{growth}}{N_i^{max}}\right)$ so the number of sites susceptible to a new infestation is:

$$N_{i,t}^{in} = \left(\sum_j^n k_{j,i} \cdot N_{j,t}^{out}\right)\left(\frac{N_i^{max} - N_{i,t}^{growth}}{N_i^{max}}\right) \quad (7)$$

The proportion of transported propagules that survive is $\lambda^{survivial}$ so the number of sites receiving live LFA propagules is:

$$N_{i,t}^{introduced} = \lambda^{survivial} N_{i,t}^{in} \quad (8)$$

Incubation and establishment

We assume that newly introduced LFA propagules incubate for w=3 years before becoming established. LFA in incubation are reproducing but not spreading. While incubated, propagules can be detected with effectiveness θ^{detect}.[14]

---

[12] We assume LFA is a robust invader and thus assume to no Allee effects (increased survival with a greater number of individuals).

[13] Leung et al. (2002) refers to this as the "base rate invasion probability"

The number of sites with incubating infestations of LFA $N_{i,t,0}^{incubate}$ (that can be destroyed) equals new introductions $N_{i,t}^{introduced}$ plus new LFA growth $N_{i,t-1}^{growth}$ less the number of sites that escaped detection, for w = 0:

$$N_{i,t,0}^{incubate} = \left(N_{i,t}^{introduced} + N_{i,t-1}^{growth}\right)\left(1 - \theta_{i,t}^{detect}\right) \tag{9}$$

For $w = 1, 2, 3$:

$$N_{i,t,w}^{incubate} = N_{i,t-1,w-1}^{incubate}\left(1 - \theta_{i,t}^{detect}\right) \tag{10}$$

After 3 years at one site, we assume LFA populations become established. Further they become numerous and problematic and readily detectible and thus subject to mitigation treatments.

The number of sites with established infestations $N_{i,t}^{establish}$ is equal to the number of treated infestations $N_{i,t}^{known}$ times the proportion that survived mitigation treatment where $\theta^{mitigate}$ is the effectiveness of mitigation treatment:

$$N_{i,t}^{establish} = N_{i,t}^{known}\left(1 - \theta_{i,t}^{mitigate}\right) \tag{11}$$

The number of sites with known LFA infestations $N_{i,t-1}^{known}$ is equal to the sites with LFA that survived three years of incubation $N_{i,t,4}^{incubate}$ plus the number of sites where LFA was found with early detection measures $\sum_{w=0}^{3} N_{i,t,w}^{incubate} \frac{\theta_{i,t}^{detect}}{\left(1-\theta_{i,t}^{detect}\right)}$ plus number of sites with established infestations from the previous time period $N_{i,t}^{establish}$

$$N_{i,t}^{known} = N_{i,t,4}^{incubate} + N_{i,t-1}^{establish} + \sum_{w=0}^{3} N_{i,t,w}^{incubate} \frac{\theta_{i,t}^{detect}}{\left(1 - \theta_{i,t}^{detect}\right)} \tag{12}$$

Total number of infested sites

Within sector i, the total number of infested sites where LFA are established, introduced, or growing is:

---

[14] Our model assumes under current management, isolated infestations detected while in incubation will be destroyed.

$$N_{i,t}^{final} = N_{i,t}^{establish} + N_{i,t}^{unknown} + N_{i,t}^{growth} \tag{13}$$

The number of infested sites at the end of year t provides the starting value for year t+1

$$N_{i,t+1}^{start} = N_{i,t}^{final} \tag{14}$$

$$Total\ infested\ sites = \sum_{t=0}^{35}\sum_{i=1}^{n} N_{i,t}^{final} \tag{15}$$

Impact submodel

The Impact submodel measures the effect of LFA infestation on the Big Island including damages (economic and social) and the cost of management.

Total Cost

Total cost associated with LFA infestation is defined as the discounted sum of economic damages $D_{i,t}$ and management costs $M_{i,t}$ over time t as follows:

$$Total\ Cost = \sum_{t=0}^{35} \delta_t \left(\sum_{i=1}^{n} D_{i,t} + M_{i,t} \right) \tag{16}$$

Where d is the discount rate and $\delta_t = 1/(1+d)^t$.

Economic damages

Economic damages are sector-specific and vary with the size and extent of the LFA infestation. Economic damages are based on estimated mean impacts from LFA and assumed to increase with level of infestation. The economic damage in sector i at time t is:

$$D_{i,t} = c_i^{damage} \cdot \frac{{N_{i,t}^{final}}^2}{N_i^{max}} \tag{17}$$

Here c_i^{damage} is the average economic damage of an infested site in sector i; $N_{i,t}^{final}$ is the number of infested sites in sector i at the end of time t; N_i^{max} is the number of sites in sector i that are susceptible to LFA. Thus, when sector i becomes fully infested, $N_{i,t}^{final} = N_i^{max}$ and annual damage is $c_i^{damage}\ N_i^{max}$.[15]

Management costs

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

$$M_{i,t} = c_{i,t}^{mitigate} + c_{i,t}^{prevent} + c_{i,t}^{detect} \tag{18}$$

The management cost is a function of management goals, management decisions, labor costs, material costs, and managed area. Mitigation treatments are applied to known infestations $N_{i,t}^{known}$. Prevention and detection activities occur at uninvaded sites $\left(N_i^{max} - N_{i,t}^{known}\right)$.

Mitigation

Mitigation expenditure $c^{mitigate}$ is a function the unit cost of mitigation $p_i^{mitigate}$, number of treatments per year $d_{i,t}^{mitigate}$, number of infested sites $N_{i,t}^{known}$ and acres per site β_i:

$$c_{i,t}^{mitigate} = p_i^{mitigate} \cdot d_{i,t}^{mitigate} \cdot N_{i,t}^{known} \cdot \beta_i \tag{19}$$

Prevention

Prevention expenditure $c^{prevent}$ is a function of unit cost $p_i^{prevent}$, number of infested sites $N_{i,t}^{known}\ and$ prevention effort $d_{i,t}^{prevent}$

$$c_{i,t}^{prevent} = p_i^{prevent} \cdot N_{i,t}^{known} \cdot d_{i,t}^{prevent} \tag{20}$$

Detection

Detection involves finding unknown infestations, so search area includes "uninfested" sites $\left(N_i^{max} - N_{i,t}^{known}\right)$. Detection effort is given by $d_{i,t}^{detect}$ and the unit cost per site is $p_{i,t}^{detect}$. Detection expenditure is expressed as:

---

[15] This functional equation is similar to the one used by Mehta, et al. (2007).

$$c_{i,t}^{detect} = p_{i,t}^{detect} \cdot \left(N_i^{max} - N_{i,t}^{known}\right) \cdot d_{i,t}^{detect} \tag{21}$$

The model is parameterized using current technology, prices, and best management practices. Management technology is assumed constant over time.

LFA Stings

Due to LFA's small size and tiny mouth parts, people are typically stung multiple times before they realize it. Further, while LFA stings are very painful, people's reaction vary widely. Therefore, we quantify LFA sting incidents of children, adults, visitors, and pets per sector per day. Further we omit the money metric and evaluate sting incidents separately from economic damages and costs.

Human sting incidents

Sting incidents are based on human population, employment by sector, and infestation in each sector. The human population $P_{i,t}$ subject to LFA stings includes both residents and visitors. Residents include adults and children. Resident population and visitor numbers are projected to rise over time. Adults are stung while at home, at work, and during leisure activities. Children are stung at home, at school and at play. Visitors are stung at lodging facilities and at play. The number of LFA sting incidents per year $S_{i,t}$ is dependent on population $P_{i,t}$, the level of infestation, $\frac{N_{i,t}^{final}}{N_i^{max}}$, the daily probability of being stung while in an infested area $\lambda_{i,t}^{sting}$, times days per year:

$$S_{i,t}^{human} = \lambda_{i,t}^{sting} \cdot N_{i,t}^{final} \cdot \left(\frac{N_{i,t}^{final}}{N_i^{max}} \cdot P_{i,t}\right)(365 \text{ days}) \tag{22}$$

Over 35 years, total human sting incidents is:

$$Total\ human\ sting\ incidents = \sum_{t=0}^{35} \sum_{i=1}^{n} S_{i,t}^{human} \tag{23}$$

Working conditions and land-use characteristics are used to determine the sting incident rate $\lambda_{i,t}^{sting}$. For example, nursery workers are in constant contact with plants will typically be stung more frequently than hotel workers will. Sting incident frequency increases with the extent of LFA infestation.

Pet sting incidents

The number of pet sting incidents per year is dependent on P^{pets} the number of domestic dogs and cats, pet sting incident frequency per day λ^{pets}, and level of infestation in i=residential:

$$S_t^{pet} = \lambda^{pets} P_t^{pets} N_{i,t}^{final} \left(\frac{N_{i,t}^{final}}{N_i^{max}} \right) (365 \text{ days}) \tag{24}$$

Model decision variables, parameters, indices

The decision (or control) variables determine the type and level of management effort in each sector at each time period. The decision variable, $d_{i,t}^{(\dots)}$, determines the level of effort in detection, prevention, and mitigation within the i^{th} sector at time 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 $0 \leq d_{i,t}^{mitigate} \leq 4$.

There are seven economic and social sectors included in the model, $i, j \in \{1, .., 7\}$. The model time horizon is 35 years, $t \in \{0, \dots, 35\}$. Outcome probabilities must be between zero and one, $0 \leq \lambda^{(\dots)} \leq 1$ and $0 \leq \theta^{(\dots)} \leq 1$, here the superscript in the parentheses denotes the phase within the biological submodel and type of management activity.

The bioeconomic model parameters and variables are defined in Table 1.

Table 1 Bioeconomic model variables, parameters, and indices

Type	Name	Description	Constraints, Bounds
Model Parameters	i, j	Indices denoting economic sector	$i, j \in \{1,..,7\}$
	t	Index denoting year	$t \in \{0, \dots, 35\}$
	λ^{growth}	Internal growth rate	$\lambda^{growth} = 0.30$
	$\lambda_i^{invasion}$	Probability that an infestation at a site in sector i will spread to another site	$\lambda_i^{invasion} = 0.115$
	$\lambda_j^{survival}$	Probability that a newly introduced infestation will survive	$\lambda_j^{survival} = 0.10$
	$k_{i,j}$	i, j^{th} entry of the dispersal kernel of the transfer matrix	$0 \leq \mathrm{k_{i,j}} \leq 1$
	$\lambda_{i,t}^{detect}$	Base probability of successful detection for 40 man hours of detection activities	$\lambda_{i,t}^{detect} = 0.25$
	$\lambda_{i,t}^{mitigate}$	Base probability of successful mitigation after one application of mitigation treatment	$\lambda_{i,t}^{mitigate} = 0.40$
	$\lambda_{i,t}^{prevent}$	Base probability of successful prevention for 40 man hours of prevention activities	$\lambda_{i,t}^{prevent} = 0.25$
	$p_i^{mitigate}$	The mitigation cost associated with one application of chemical mitigation per acre, in sector i	None
	$p_i^{prevent}$	The per unit cost of prevention per site in sector i	None
	p_i^{detect}	The per unit cost of detection per site in sector i	None
	β_i	A conversion factor that translates the number of sites in sector i into acres	None
Biological submodel	$N_{i,t}^{(\dots)}$	Infestation extent for a given phase of the biological submodel, measured in the number of infested sites	$N_{i,t}^{(\dots)} \geq 0$
	$N_{i,t}^{start}$	Infestation extent at year t in sector i, measured in the number of sites	Same as above
	$N_i^{initial}$	The starting infestation extent $t = 0$ in sector i measured in the number of sites	Same as above
	$N_{i,t}^{growth}$	Infestation extent due to internal growth within sector i, measured in the number of sites. This does not include spread from other sectors, or effects of management.	Same as above
	N_i^{max}	Infestation carrying capacity measured by the number of sites in sector i	Same as above
	$N_{i,t}^{out}$	The amount of outgoing spread that leaves sector i at time t (i.e., the outgoing spread), measured in the number of sites.	Same as above
	$N_i^{introduced}$	Number of sites in sector i at a time t that are susceptible a LFA introduction	Same as above
	$N_{i,t}^{in}$	Number of sites in sector i at a time t receiving incoming spread	Same as above
	$N_{i,t,w}^{incubate}$	Number of sites (at a sector i and time t) that are	Same as above

		incubated (i.e., have viable infestations, but are not detected), where w denotes the index year of being incubated.	
	$N_{i,t}^{unknown}$	The number of sites that without a known infestation, which could include sites with an incubated infestation, and those sites without any infestation.	Same as above
	$N_{i,t}^{known}$	The number of sites with a known infestation. Since these infestations are known, these sites are susceptible to mitigation and prevention efforts.	Same as above
	$N_{i,t}^{final}$	The number of infested sites at the end of the biological submodel.	Same as above
	$N_{i,t}^{mitigate}$	The effect of mitigation treatment efforts on the number of infested sites, measured in number of sites.	Same as above
Management submodel	$d_{i,t}^{detect}$	Decision variable for detection, measured in man-hours.	$d_{i,t}^{detect} \geq 0$
	$d_{i,t}^{mitigate}$	Decision variable for mitigation treatment, measured in the number of applications per year.	$0 \leq d_{i,t}^{mitigate} \leq 4$
	$d_{i,t}^{prevent}$	Decision variable for prevention, measured in man-hours.	$d_{i,t}^{prevent} \geq 0$
	$\theta_{i,t}^{detect}$	Effectiveness of detection measured in the probability that an incubated infestation is detected	$0 \leq \theta_{i,t}^{detect} \leq 1$
	$\theta_{i,t}^{mitigate}$	Effectiveness of the mitigation treatment efforts, measured in the probability that an infested site is successfully eradicated	$0 \leq \theta_{i,t}^{mitigate} \leq 1$
	$\theta_{i,t}^{prevent}$	Effectiveness of prevention measured in the probability that prevention efforts will successfully stop infestations from spreading	$0 \leq \theta_{i,t}^{prevent} \leq 1$
Impact Submodel	$D\left(N_{i,t}^{final}\right)$	Damage cost as a function of the final infestation extent, which includes economic damages (e.g., production losses, reduced worker productivity, loss of nursery export sales), and ecosystem service damages	None
	$M_{i,t}$	The total cost of management alternatives for sector i at time t	None
	$c_{i,t}^{damage}$	Per site damage cost for sector i	None
	$c_{i,t}^{mitigate}$	The cost of mitigation treatment for sector i at time t	None
	$c_{i,t}^{prevent}$	The cost of prevention for sector i at time t	None
	$c_{i,t}^{detect}$	The cost of detection for sector i at time t	None
	$S_{i,t}^{human}$	The number of human related LFA sting incidents in sector i at time t.	None
	$P_{i,t}$	The human population of the big island within sector i at time t	$P_{i,t} \geq 0$
	$S_{i,t}^{pet}$	The number of pet related LFA sting incidents in sector i at time t	None

Empirical Data

To parameterize the bioeconomic model, we gathered primary data through surveys and interviews, acquired ongoing time series data on LFA, and supplemented with government statistics.

Current infestation

Using data on a series of online surveys by the Hawaii Ant Lab, we estimated number of infested locations and acreages on the Big Island. The number of susceptible sites (i.e., the sector capacity) was based on information from 2007 Census of Agriculture, the 2011 Visitor Plant Inventory, City-data.com, and the State of Hawaii Data Book. Current infestation for our model baseline appears in Table 2.

Table 2 LFA infested locations on the Big Island 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	52216
Parks	3.9%	6	152
Schools	1.2%	1	84
Other	1.7%	568	32547

Spread mechanism

We evaluated economic activity on the Big Island to estimate annual spread of LFA within and between sectors. While some movement of LFA between businesses and residences would be via commerce, we also included transfer of LFA hitchhiking on employees as they commuted between home and work. In 2010, there were 80 thousand jobs on the Big Island, 2% each in the agriculture and nursery sectors, 8% each in the lodging and park sectors, 21% in the school sector, and 58% in all other. Thus, of the LFA transferred from infested residences, a larger portion would be introduced to the lodging sector than the nursery sector and so on. Number of children was used to estimate transfer of LFA between schools and residential areas. Commerce activity was used to estimate transfer between commercial sectors and all other sectors. The transfer matrix takes new LFA growth from infested areas and distributes the LFA proportionately across sectors as shown in Table 3.

Table 3 Proportionate distribution of new growth within and across sectors, from i to j

		Sector *i*						
		Nursery	Ag	Lodging	Residential	Parks	Schools	Other
Sector j	Nursery	35%	5%	2%	0%	2%	2%	10%
	Ag	5%	35%	1%	0%	2%	2%	10%
	Lodging	2%	5%	30%	2%	10%	2%	10%
	Residential	21%	22%	30%	90%	65%	75%	20%
	Parks	2%	2%	30%	1%	15%	15%	1%
	Schools	1%	1%	2%	1%	5%	2%	0%
	Other	35%	31%	5%	6%	1%	2%	49%
	Total	100%	100%	100%	100%	100%	100%	100%

Economic sectors

For purposes of modeling LFA spread and economic impacts, we subdivided the economy into 7 economic sectors – agriculture, nursery, residences, schools, lodging, parks, and all “other” as depicted in Figure 7.

Figure 7 Economic sectors defined in the Impact sub-model

We developed a database to characterize the relevant components of each sector at the present time and projected into the future. Where available, we use secondary data from government databases (e.g. US Census Bureau, USDA, DOI, etc.) and published reports. For the remainder we collected primary data using surveys, interviews, and expert input.

Agriculture

In 2008, agricultural sales on the Big Island totaled $193 million with $137 million in crop sales, $28 million in livestock sales, and $28 million in aquaculture sales. Sales from the Big Island (BI) represent nearly one-third of all agricultural sales in the State of Hawaii. Big Island agricultural sales in 2008 are displayed in Table 4.

Table 4 Annual agriculture sales in Hawaii and on the Big Island

	Agriculture Sales 2008[16]	
	Hawaii State	Big Island
	$1000	
Crop	$522,139	$137,086
Livestock	48,781	28,439
Aquaculture	34,650	27,836
Total	$605,570	$193,361
Livestock and crop	$570,920	$165,525

Crop. LFA indirectly affect crops by nurturing honeydew producing insects [17] which directly impair crop growth and hence yields. Some can transmit diseases which further impact yields. To reduce insect impacts and restore yields, farmers must treat for scale insects and control LFA.

Livestock. LFA harm livestock (e.g. cattle, hogs, poultry) by repeatedly stinging animals causing pain and discomfort. When animals are uncomfortable their growth slows; they gain less weight, milk output decreases, and egg output declines.

Aquaculture. There are no known LFA impacts to aquaculture crops. For this study, we assume no economic damages to aquaculture.

Economic damages. At the time of this study we were unable to locate prior work quantifying the yield impacts from LFA. Based on our experience with crop pests, we assumed that if left

---

[16] HDOA and NASS, Statistics of Hawaii Agriculture 2009, Jan 2011, 101 pp, Weblink http://www.nass.usda.gov/Statistics_by_State/Hawaii/Publications/Annual_Statistical_Bulletin/2009.pdf

[17] Parasitic insects that feed on plant sap. Examples are aphids, white flies, mealybugs, and scales.

untreated, LFA would reduce agricultural yields 0% to 50% and damages to agriculture would be 20% to 30% of sales, or $33 to $50 million per year.

Nursery

To assess the impact of LFA infestation on BI nurseries, in 2011 we conducted an industry wide survey. During the summer of 2011, we developed and pre-tested a survey instrument to ascertain the current infestation, quantify damages, and learn their approach to control. In August 2011, with the help of a Big Island Association of Nurserymen (BIAN) officer, our study was mentioned during a BIAN meeting. Following the meeting our survey was distributed via an email link to members of Hawaii Export Nursery Association (HENA), BIAN, and Hawaii Floriculture and Nursery Association (HFNA). Within a few days later, members received a follow-up reminder email.

We received a survey response from 27 members of the nursery industry representing $16-29 million in industry sales grown on 468 acres. The total industry size is 1,530 acres with annual grower sales of $41 million[18], so our survey captured 31% of operating acreage and up to 70% of production on the Big Island.

Among our survey respondents, 23 had previously tested for LFA; 10 nurseries test their property, products, and purchases regularly - weekly, bi-annually, annually, or as needed; 4 operators reported that they have never tested for LFA.

Three nurseries reported finding LFA in the past but are currently LFA free. One nursery reported having a current LFA infestation but not actively treating it. Three nurseries in Hilo and Puna were treating small isolated LFA infestations with the intent of preventing spread and eradicating. They estimated the infestation would take 1-2 years to eradicate and reported that they were spending $1200 per year.

The average operation size of respondents was 17 acres with 7 acres in production and 9 employees. For this question we had 17 responses and 6 non-responses.

The average size of operations of respondents reporting an LFA infestation was 10.5 acres with 8 acres in production and 2 employees. For this question we had 2 responses, 2 non-responses.

Exports. Commercial trade is vital to Hawaii. The major exported agricultural commodity groups were cattle, flowers and nursery products, molasses, sugar, and seeds valued at over $500 million

---

[18] NASS, 2011, p. 11-12

per year[19] in 2010. In excess of 70% of the value of good produced in Hawaii was exported to the U.S. mainland. If a LFA invasion becomes well established in Hawaii, other locations are likely to impose preventative measures to minimize the spread of the LFA. These preventative actions will inhibit trade and thus harm Hawaii's export economy. For example, the presence of the LFA on exported fruits and vegetables from Hawaii could cause rejection and return shipment to Hawaii (Costa et al., 2005; Follett & Taniguchi 2007 in Souza et al., 2006 cited in Invasive Species Specialist Group, 2009).

*Economic damages***.** At the time of this study we were unable to locate prior work quantifying the yield impacts from LFA. The nursery exports are highly sensitive to introduced and invasive species. Based on industry observations, we assumed that if left untreated, local sales would be unaffected and export sales would decrease 50% for a loss of $9,109 per infested farm.[20]

Lodging

To characterize the effect of an LFA infestation on the Big Island lodging sector, we also conducted an industry wide survey. In fall 2011, we developed and pre-tested an online survey instrument to assess the extent of LFA infestation, damages from infestation, and control measures used. During December 2011, with help from Hawaii Lodging and Tourism Association HTLA[21], the LFA study was described to HLTA members during a quarterly meeting. A few days later, HTLA emailed a link to the survey to managers of hotels, condos, timeshares, and bed and breakfast establishments. Over the course of two months, two email reminders were sent. As well, we phoned the managers of three large Hilo hotels.

We received survey responses from seven Big Island lodging representatives (managers, executives, administrators, and an owner). The responses represented 2000 guest rooms and residences on the Big Island, 29% of the guest rooms on the Big Island[22].

One respondent reported finding a previous LFA infestation in landscaping but had it eradicated, and the remainder had never been infested. At the time of the survey, none of our respondents were infested with LFA and none were treating an infestation. Two respondents reported that

---

[19] Values are estimated. The total value of exports were not published in the Statistics of Hawaii Agriculture for years 2009 and 2010.

[20] Average LFA damage per farm is estimated to be 50% of farm exports sales $13.791 million total sector sales divided by 757 farms

[21] Tina Yamaki, Executive Director HLTA

[22] In 2011 Big Island inventory was 6,811 guest rooms. Guests stay an average of 4 days and pay $175 per night. http://hawaii.gov/dbedt/info/visitor-stats/visitor-plant/2011VPI.pdf

their property had been tested for LFA, five reported that their property had never been tested for LFA.

All respondents expressed concern about LFA believing that an infestation could result in reduced guest satisfaction, reduced bookings, loss of repeat business, and tarnished reputations. One respondent expressed confidence in the pest control service to monitor for LFA and treat any infestation before it could cause a problem.

To prevent an LFA infestation, one respondent purchases plants only from certified growers and tests new plants before installing them on the property. Two respondents expressed concern, but were not doing anything to prevent LFA. Two respondents said they were not concerned about LFA.

In the event of an LFA infestation, all respondents would treat the infestation either using in-house staff or a professional pest management firm.

Pest management is a routine function at Big Island lodging facilities. All of our respondents employ a pest management firm for regular scheduled maintenance of indoor pests and additionally contacts a pest management firm and uses in–house staff as needed. For outdoor pests, four employ a pest management firm for scheduled maintenance and one employs a pest management firm only as needed.

Our respondents included hotels, condominiums, timeshares, and a B&B in the Kona, Kohala, and Hilo areas with an average room rate of $208 per night. They reported peak season occupancy of 60% to 80% and low season occupancy of <40% to 70%.

Economic damages. At the time of this study we were unable to locate prior work quantifying the impact of LFA on lodging revenues. Our conjecture is that the Hawaii lodging sector is moderately sensitive to biting and stinging insects. Guests tend to spend a lot of time outdoors, both on and off property where they are exposed to a variety of insects. We assume that if left untreated, repeat business would decrease causing revenue reductions of 20% for an average loss of $183,259 per property.

Residential units on the Big Island

Total housing units on the Big Island including detached single-family dwellings, townhouses, and condominiums with 1-20 or more units per structure was 62,287 in 2009. We estimate total housing units in 2012 to be 52,216. In 2010 and 2011, 4,249 homes were sold on the Big Island, and the mean sales price was $248,538 as shown in Table 5.

Table 5 Home sales in Big Island (Hawaii County)[23]

Big Island homes sales in 2010-11					
	Price		No. Sales		Mean Price
	2010	**2011**	**2010**	**2011**	2010-11
Single family	$255,000	$242,500	1509	1616	$248,750
Condos	$270,000	$225,900	521	603	$247,950
Total			2030	2219	

Economic damages. The residential sector is moderately sensitive to stinging and biting insects. If left untreated, homeowners will suffer a reduction in home value; a loss in the use and enjoyment of outdoor areas (e.g., home gardens, hobby yard work, playing, lounging); and a disruption in home life from repeated stings indoors. Since home sellers would be legally obligated to declare a LFA infestation and/or treat the property prior to sale, there will be a cost to home sellers or a reduction in property values. We estimate the loss of property value due to an LFA infestation will range from $300 per unit sold if the infestation is treated before the sale, and $750 per unit sold if no treatment occurs before sale. Of the 27,522 residential property units on the island of Hawaiʻi, about 2,125 are sold annually. We assume the probability of selling a house is independent of the likelihood of being infested, thus the expected loss in property values in this sector would be about $23 per unit sold (i.e., $23 = $300*2125/27,522) if treated, and about $58 if not treated. For damages due to loss of use and enjoyment of outdoor areas, we estimate that the value of the complete loss of a home yard for entertaining and recreating is $1,023 to $1,058 per household per year,[24] including the recreational value of home gardening but not the value of products produced.[25]

Homeowner response to LFA

In fall 2012, we developed and pre-tested an online survey instrument to better understand homeowner response to LFA. We focused our attention on a housing development in Puna that had discovered an LFA infestation and was preparing to organize a group response. The Puna Beach Palisades (PBP) owners association was interested in our study and agreed to collaborate.[26] Our study was described to property owners at a meeting in December 2012. At

---

[23] http://www.tghawaii.com/learning/stats/monthlystats-dec2011.html

[24] Based on travel cost to another site for two people, 1 hour, $10/hour, 50 times per year. Or based on the differential prices between homes with and without (condo) private yards, $20,000 amortized at 5% is $1000

[25] Small net gain when considering both the value of goods from the yard and labor plus inputs required to produce those goods. There is aesthetic value and exercise value from gardening, but as well a time saving from not gardening that can be shifted. Not all homeowners are garden hobbyists. Some homeowners pay for yard service.

[26] We were in communication with several property owners, but eventually worked closely with board member Rogerio Menescal of Puna Beach Palisades property owner association who had volunteered to lead the PBP LFA

that meeting, 15 members in attendance provided their emails on a sign-up sheet. During February 2012, emails with a link to the survey were sent to the 15 people; and our survey link was forwarded to 67 members on the PBP mailing list.

Over the course of a few days, we received nine responses to the survey[27]. Of those, seven have LFA on their property and two previously had LFA on their property. All seven have LFA outdoors in natural vegetation, landscaping, and gardens, four have LFA inside their homes. Indoors, homeowners have been finding LFA in all areas of the house.[28] All respondents reported having been stung by LFA. They described the sting as painful, burning, itching, like an electric shock; the sting left a mark that was red and swollen.

Four provided these additional responses

- *We get bitten almost daily from leaning on the kitchen counters or from picking up something they are on, like a kitchen towel*
- *Two of my six cats apparently have been stung by fire ants in their eyes (cloudy eye) one is an indoor house cat mostly, the other goes all the way down the street at the end of Kipuka Street where care-taker told me when retrieving the cat to watch for fire ants as they fall in cascades down from the leaves of bushes and trees there and I should be fully covered from head to toe!*
- *I work in my yard and stay alert for them. They aren't everywhere but plenty around*
- *Always got stung when brushing up against mango trees or other plants. They would fall down on me. Now I have the yard treated monthly with Amdro.*
- *Allergic reaction requiring prednisone treatment*

Six replied that they were treating LFA and 2 said they were not. Reasons for treating LFA included: to protect themselves, family and guests from stings; to protect plants and pets, and to prevent LFA from spreading. Spending ranged from $300 to $600 per year per household since 2010.

To prevent a new infestation, one household purchases plants from certified growers and three test all new plants before installing on the property. Four treat the border between their property and their infested neighbor, two are concerned but are doing nothing to prevent infestation.

Four wrote these concerns

---

response effort – gathering information, scheduling speakers, coordinating and communicating with property owners.

[27] The low response may be due to a misunderstanding as several homeowners told us they thought only properties with an LFA infestation were supposed to complete the survey. The infestation at PBP affects only a few lots.

[28] LFA have been found in the bedroom, pool, entryway, dining room, living room, family room, kitchen, bedroom, laundry room, washroom, front and back porch, driveway, and pantry

- *I am frustrated and don't really know what to do. They are every where and I am afraid to use poison around my granddaughter who lives with us.*
- *I am concerned since I live next to big Kipuka and there are empty lots next door and have six cats and have little income. We believe there could be infestation of these ants inside our f[F]ord explorer vechicle [vehicle] on property which raises stress level[s] as we just bought and shipped [the] vehicle over from Oahu in August 2011*
- *I treat around my house and when I find nests. I will broadcast poison*
- *I will ask the n[e]ighbors if we can all treat the permiter [perimeter].*

For indoor LFA, six are using commercial insecticides and baits and one is using homemade or natural remedies. None have hired a pest control company. For outdoor LFA, seven are using commercial insecticides and baits, one is using homemade or natural remedies, one hired a professional pest company.

For other (non-LFA) indoor pests, eight households use commercial insecticides and baits, none use homemade or natural remedies, none hire a pest control company, and one does not treat indoor pests. For other (non-LFA) outdoor pests, four use commercial insecticides and baits, one uses homemade or natural remedies, none hire a pest control company, two do not treat outdoor pests.

All of our survey respondents own a single family home in Puna - either a studio, 1, 2, or 3-bedroom home. All but 1 are full time residents, 1 has a home in Honolulu and lives in Puna on weekends.

Schools

In the "schools" sector, we included the following categories of publically used buildings: schools, universities, churches and a post office. For the Big Island we include a total of 84 properties.

Parks

In the "parks" sector we included the following categories of publically used outdoor spaces: parks, beaches, camps, ranches, cemeteries, lakes, reservoirs, swamps, streams, rivers, creeks, and wildlife and hunting areas. For the Big Island we include a total of 152 properties.

Parks (Ecological impacts from LFA)

In Hawaii LFA have been observed infesting honey bee hives. The cause of the hive destruction has not been studied, but scientists have observed a clear pattern between LFA infested areas and dead hives. Background information appears in Box 3.

Box 3. LFA impact on Big Island Honey Bees

In 2012, a beehive on the Big Island was found infested with LFA. LFA were on the inside and the outside of the hive. Entomologist Lorna Tsutsumi speculated that LFA took honey for food which led to a reduction in brood production and allowed a secondary invader (e.g. wax moth) to enter and destroy the hive. Ecologist Cas Vanderwoude confirmed that LFA will take all of the honey and kill bees in the process. Eventually the hive will die. The surest means to protect the hive is to move the hive to an uninfested location. Farm manager Diki Short relocated the farm's managed hives to an area out of the forest and clear of overhanging trees.

Source: Per email and phone communication with Lorna Tsutsumi, Cas Vanderwoude, and Diki Short in October 2012.

Hawaiian nēnē geese reproduction may be threatened by LFA. Chris Costa[29] observed nene nests with abandoned hatchlings and an infestation of LFA on the Big Island. Chris conjectures that the parents may have been chased from the nest by mongoose and rats.

Additional ecological impacts of LFA in New Caledonia and West Africa were documented in several prior studies as shown in Table 6.

---

[29] sekrah@me.com

Table 6 Ecological impacts from LFA

Animals studied	LFA impact	Location	Source
Reptile populations	Decrease in population in invaded areas	New Caledonia	Jourdan et al 2001
Scorpions, spiders, invertebrates	Eliminated or reduced	New Caledonia	Lubin 1984
Pseudoscorpions	Excluded from invaded areas	New Caledonia	Jourdan 1997
Terrestrial invertebrates	Partial exclusion from invaded areas	New Caledonia	Jourdan 1997
Caspid bug (*sahlbergella singularis*)	Reduces mirids and other insects	W. Africa	Entwistle 1972

Source: Holway et. al. 2002

Parks (Ecosystem service value of parks)

Based on a meta-analysis, de Groot, et al. (2012) estimated the mean value of the world's tropical forests to be $14,138 per year per acre. Based on impacts in Hawaii and around the world, LFA is likely to reduce pollination services, weaken genetic diversity, and reduce recreational opportunities; the combined value of these services is conservatively estimated at $2,523 per acre per year. We estimate an LFA infestation could result in a service loss of 1% to 30% or $25 to $757 per acre per year. Ecosystem service values for tropical forests are shown in Table 7.

Table 7 Ecosystem service value of tropical forests

	2007*	2012**	2012		
			% service loss with LFA infestation		
Services	*$ per ha per year*	*$ per ac per year*	1%	10%	30%
			$ per ac per year		
Pollination	$30	$13.5	$.1	$1.3	$4.0
Genetic Diversity	$23	$10.3	$.1	$1.0	$3.1
Recreation	$867	$389.5	$3.9	$38.9	$116.8
Relevant services		$413.3	$4.1	$41.3	$124.0
Other services		$1,951.3			
All services	$5,264	$2,365.6			

*Source Rudolf de Groot, et. al. 2012
**1 hectare = 2.47105 acres. $1 in 2007 = $1.11 in 2012 (BLS, 2013)

Table 8 Summary of LFA sector damages

Sector	Description of damages	Damage value
Agriculture	Reduced productivity	$583 per farm
Nursery	Loss of export sales	$9,110 per farm
Lodging	Reduced revenue from lower occupancy rates	$183,259 per property
Residential	Reduced property value Reduced use of outdoor areas	$1,023 to $1,058 per residential unit
Parks	Ecosystem service loss	$2365.6 per acre
Schools	Reduced use of indoor and outdoor areas	n.a
Other	Reduced revenue	$533 per business

LFA Sting incidents

Humans are stung at work, at home, at school and at play. Pets are stung at home. A graphical display of sting locations appears in Figure 8.

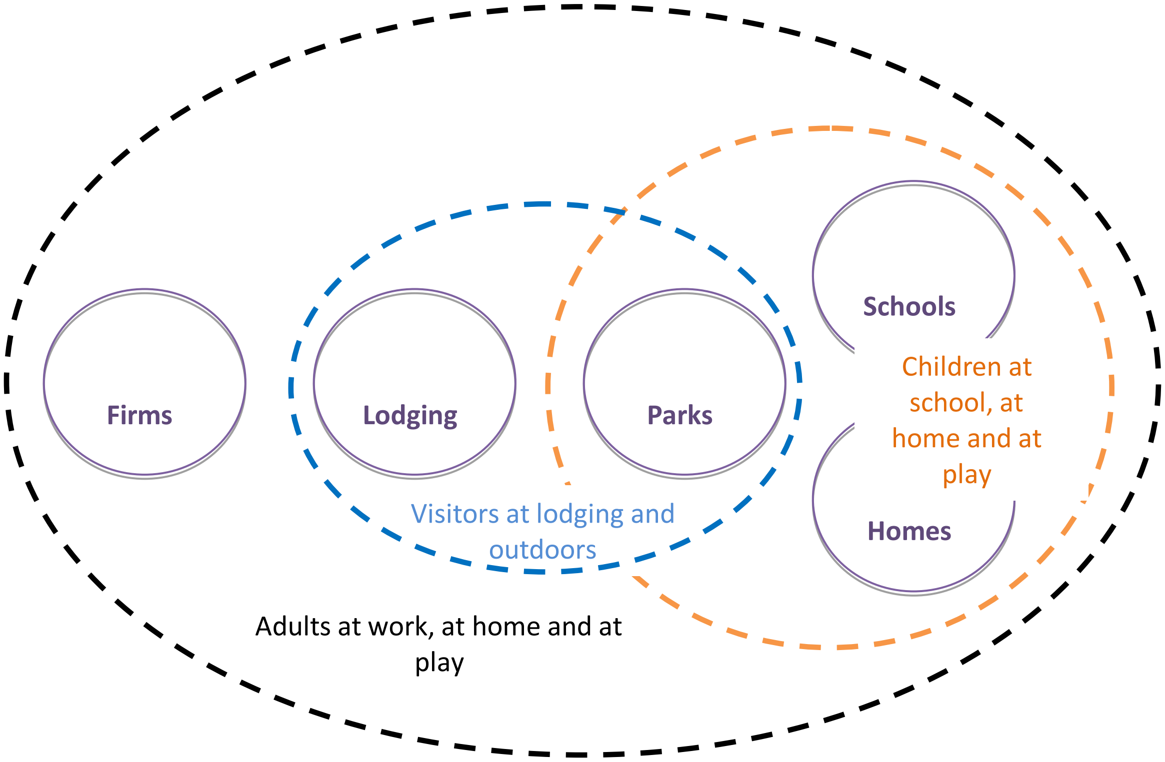


Figure 8 Where people are stung

Human stings

To count the number of sting events, we looked at the primary locations where people are likely be stung. Then we collected data to assess the number of people and exposure frequency assuming the people would continue to spend time in those areas after the areas are infested.

Population The resident population on the Big Island was 176,700 in 2010 growing to 279,700 by 2035. Population projections are based on US Census data and Hawaii County population projections. The 2009 resident population includes 43,745 children on the Big Island. Daily visitor numbers were obtained from the Hawaii State Dept. of Business, Economic Development, and Tourism (DBEDT). A population projection for the Big Island is illustrated in Figure 9.

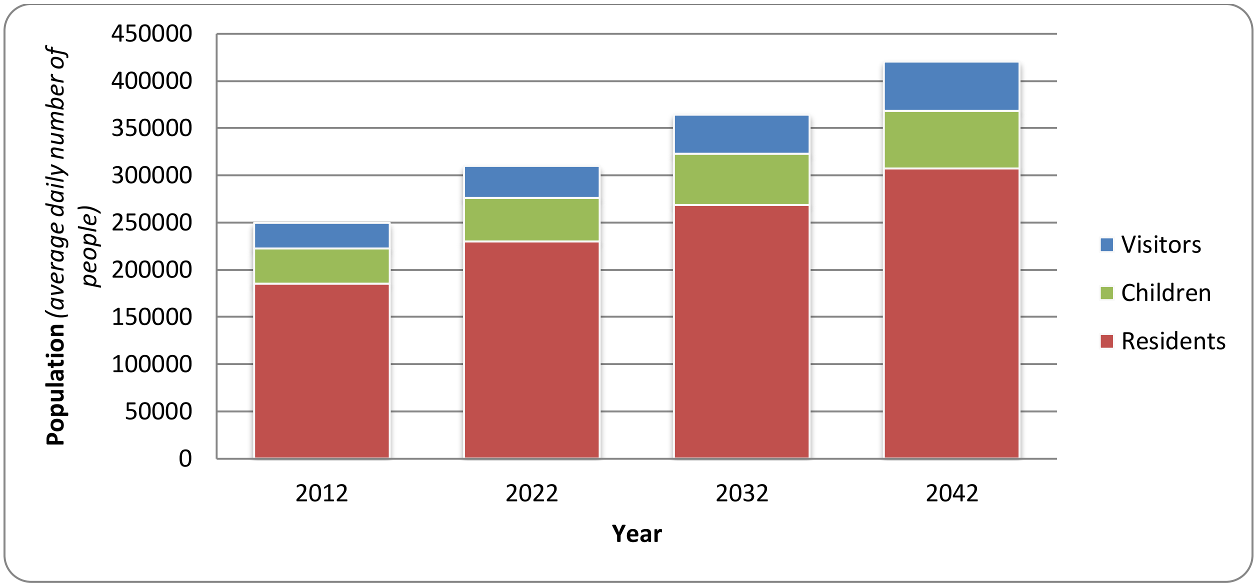


Figure 9 Big Island population, 2012-2042

Housing Total housing units is estimated to be 52,216.[30] Median value of detached houses and condos is $349,300. Mean household size is 2.8 persons per home.

Employment Employment per sector was used to estimate stings at work.[31] Sector and total employment projected for the Big Island is displayed graphically in Figure 10.

---

[30] Housing unit from 2009 "City Data".

[31] http://records.co.hawaii.hi.us/Weblink8/Browse.aspx?startid=27952&dbid=1

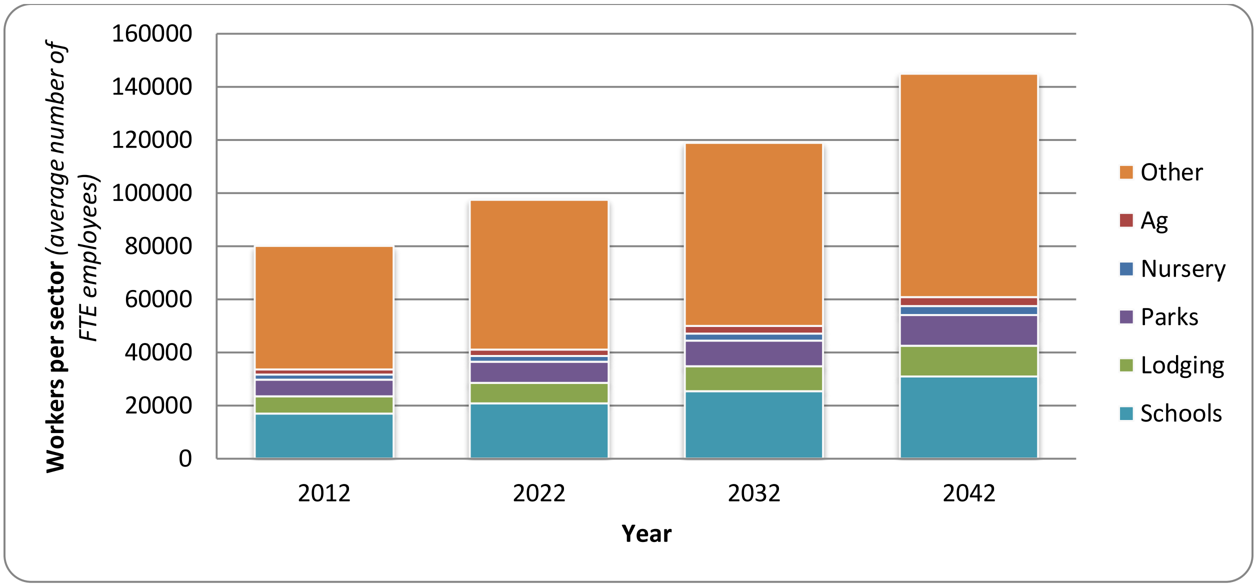


Figure 10 Big Island employed population, 2012-2042

Recreation Outdoor recreational activity was used to estimate number of people exposed to LFA stings in parks. Number of people engaging in outdoor recreation activity each day is shown in Figure 11.

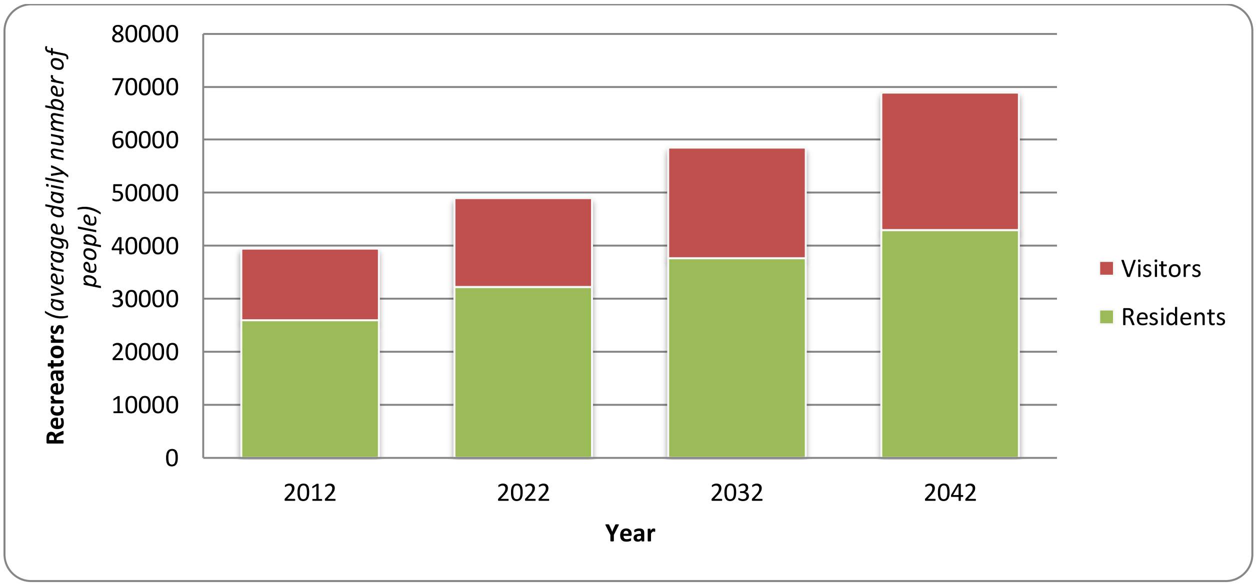


Figure 11 Big Island recreational participants, 2012-2042

Hawaii visitor participation in hiking, backpacking, and camping is 25%; visits to cultural parks and gardens are 58%, time spent at the beach swimming and sunbathing is 83%. [32] We estimated that 50% of all Big Island visitors will spend some time in outdoor recreation in parks or at beaches. We assumed 14% of the resident population is visiting a park or beach on any given day of the week.

In the agricultural, nursery, and park sectors, we assumed employees will be stung once per week at lightly infested work sites and five times per week at heavily infested work sites.

In lodging, school, and other sectors, we assumed 20% employees will be stung once per week at lightly infested work sites and 20% of employees will be stung five times per week at heavily infested work sites.

At lodging facilities, we assumed 10% of visitors will be stung once per week at lightly infested facilities and 10% of visitors will be stung seven times per week at heavily infested facilities.

At schools, we assumed 20% of children will be stung once per week at lightly infested locations and 20% of children will be stung five times per week at heavily infested locations. At homes, 33% of children will be stung once per week at lightly infested properties and 37% will be stung seven times per week at heavily infested properties.

In homes, 33% of residents will be stung once per week at lightly infested properties and 37% of residents will be stung seven times per week at heavily infested properties.

Pet stings

The number of pets (dogs and cats) is estimated by multiplying the number of households on the Big Island by 3.9, the average number of dogs (1.7 per household) and cats (2.2 per household) based on average pet ownership in the U.S. as shown in Table 9.

---

[32] Hawaii State Data Book, 2012, dbedt.hawaii.gov/economic/databook/db2012

Table 9 U.S. pet ownership in 2007[33]

	Dogs	Cats
Percent of households owning	37.2%	32.4%
Average number owned per household	1.7	2.2
Veterinary visits per household per year (mean)	2.6	1.7
Veterinary expenditure per household per year (mean)	$356	$190
Veterinary expenditure per animal (mean)	$200	$81

Total domestic dogs and cats on the Big Island in 2012 are estimated to be 87,180.

Sting frequency per pet is estimated to be twice the sting frequency of residents based on the assumption that residents are home about 12 hours per day and pets are home all day long. As well, pets spend more time outdoors, live closer to the ground, and sleep close to the ground.

We estimate the damage value to be $35 per year for infested households with pets based on the assumption that LFA stings will cause owners to visit a vet one additional time during a pet's lifetime.[34] Information used to compute damage estimates appear in Table 10.

Table 10 LFA pet cost calculations based on US Pet Ownership data

		Dogs	Cats
	Visits per pet	1.53	0.773
	Cost per visit	$136.92	$111.76
	Cost per pet	$209.41	$86.36
	Lifespan in years	12.8	15
	Cost per pet per year	$10.70	$7.45
Dog and cat combined	Average cost per pet for LFA	$8.97	
	Average pet cost per house with LFA	$34.99	

Control costs

Baited insecticides are recommended as the first line of attack for destroying an LFA infestation. The products combine a desirable food with a slow acting poison. The LFA take the chemical-

---

[33] Table 2 copied from website: 2007 U.S. Pet Ownership & Demographics Sourcebook, http://www.avma.org/reference/marketstats/ownership.asp

[34] http://www.vetinfo.com/average-cat-lifespan.html/

laced bait back to the nest. LFA die after ingesting the bait. Chemicals that are effective against LFA include Hydramethylnon and S-methoprene found in branded products Amdro and Extinguish. [35]

Contact insecticide is recommended for spraying potted plants to kill any existing LFA before transporting live plants. LFA die when they come in contact with the insecticide. The chemical that is effective against LFA is Carbaryl[36].

Contact insecticides are recommended as barrier treatments to kill any LFA as they try to crawl into an uninfested area. LFA die when they come in contact with the insecticide. The chemicals that are effective against LFA are Bifenthrin and Alpha-cyhalothrin[37] found in the branded products Ortho Home Defense and Triazicide Once and Done.

Amdro is applied at the rate of 1.42 lbs. per acre (Causton, Sevilla, & Porter, 2005) at a cost of about $15.50 per lb. Chemicals application requires person-hours of 1 hour per acre at $15.00 per hour, $148 per year if treated every three months for an entire year. Of course costs will vary depending on factors such as vegetation, terrain, accessibility, labor costs, etc. This figure is in the ballpark of the people we spoke to – homeowners on lots of 2 to 5 acres were spending $300-$600 per year to eliminate LFA.

Pest control operator

We spoke to several hotel managers on the Big Island regarding the approach they use for routine pest control. All said they contracted with EcoLab so the owner, Dave Lau[38] was contacted and interviewed on July 18, 2012.

Dave treats for many different kinds of ants and actually receives the most calls for ants at military facilities on Oahu. He had not yet encountered LFA on the Big Island or elsewhere and was not currently monitoring for LFA.

His current maintenance contracts with hotels do not include treatment of LFA, so an infestation would entail an additional charge to his clients. EcoLab would develop an eradication plan and then charge for services and materials. The eradication plan would be a multi-pronged approach

---

[35] Source: http://littlefireants.com/index_files/download_files/Industry/plantvendortraining.pdf

[36] Carbaryl is an activive ingredient in Bayer Sevin

[37] Bifenthrin and Alpha-cyhalothrin are active ingredients in Ortho Home Defense and Triazicide Once and Done

[38] Dave Lau, Ecolab Pest Elimination, P.O. Box 98 Aiea, HI 96701, 808-216-9282, david.lau@ecolab.com

to include: exclusion, sanitation, baiting, finding the nests, chemistries, and deterrence. Dave believes the existing treatments and chemicals are adequate for eradicating LFA from a property.

Management scenarios

To assess the potential economic damages from LFA on the Big Island and potential benefits from managing LFA, we evaluated a status quo (current management) scenario and five alternate scenarios: reduced management, least cost, least stings, and eradicate LFA.

Status quo

Status quo simulates current public and private management efforts. In the private and residential sectors, sector-wide management takes place when LFA becomes problematic which we assume to occur when infestations levels reach 20%. Management effort is proportionate with the level of infestation N_i^{final}. In the Park and School sectors LFA will remain untreated. This level of effort is assumed to minimize economic damages and costs within the managed sectors but not explicitly prevent spread to other sectors.

Reduced

Reduced management represents a decrease in future LFA management efforts: mitigation treatment, prevention and detection. In this scenario, we assume that individuals in the business and residential sectors, sector-wide manage occurs with LFA infestations become problematic, when infestation level reach 20%. Overall effort however is 20% less than the status quo.

Least cost

Optimization modeling is used to determine the management effort required to minimize (Equation 16) long-term LFA management costs and economic damages over 35 years across all economic sectors.[39]

Least stings

Optimization modeling is used to determine the management effort required to minimize (Equation 23) human sting incidents over 35-years across all economic sectors.

---

[39] For the least cost, least sting, and eradication models, we reached steady state when infestation levels converged to below 0.1% and management effort was constant for three consectutive years.

Eradicate LFA

Optimization modeling is used to determine the management effort required to minimize (Equation 15) the total number of LFA infested sites. We assume eradication efforts occur for any infestation larger than 2.5% and we declared eradication achieved when sector infestation falls below 1%. For most sectors eradication efforts yielded infestation rates of <0.1% .

Discount rate

For our analyses we referred to OMB guidelines for benefit-cost analyses of proposed federal projects. The most recent update to the guidelines was released January 2012.[40] Based on the 2012 update, the nominal discount rate r is 3.8% for a 30-year project with nominal flows and the real discount rate r is 2.0% for a 30-year project with constant flows. We used a real discount rate[41] of 2.0% for our long run simulations and conducted sensitivity analyses using discount rates of 4% and 8%.[42]

Results

Highlights

Management effort has a significant impact on LFA infestation over time. Under reduced and status quo management, LFA infestation continues to rise in all sectors: from 4.5% to 10% by year 5, and 19% by year 10. Under least cost, least sting, and eradicate LFA management, LFA infestation decreases in all sectors. Under least cost management, LFA are suppressed in 27 years. Under eradicate LFA management, LFA are suppressed in 8 years. Under least sting management, LFA is suppressed in 2 years. Table 12 summarizes the infestation levels over time for the five management alternatives.

Management effort has a significant impact on the number of LFA sting incidents over the next 35 years. With reduced management, human sting incidents are 3.4 billion and pet sting incidents are 1.9 billion. With status quo management human sting incidents are 2.3 billion and pet sting

---

[40] 2012 OMB Annual update, Memo M-12-06, http://www.whitehouse.gov/sites/default/files/omb/memoranda/2012/m-12-06.pdf

[41] Where i is the annual rate of inflation and R the nominal discount rate, the real discount rate r is derived: $r = \frac{1+R}{1+i} - 1$

[42] For comparison, the real discount rate for Federal water project cost-benefit analyses was 4% in 2012 and is 3.75% in 2013.

incidents are 0.9 billion. With least cost management human sting incidents are 94 million and pet stings incidents are 11 million. With eradicate LFA management human sting incidents are 28 million and pet sting incidents are 9 million. With least sting management human sting incidents are 6 million and pet sting incidents are 4 million. Table 11 summarizes human sting and pet sting incidents over time for the five management alternatives.

Present value total cost (combined management costs and damages) vary widely with management effort. Under reduced management, present value total cost is $12.8 billion. Under status quo management, present value total cost is $6.1 billion. Under least sting management, present value total cost is $944 million. Under eradicate LFA management present value total cost is $561 million. Under least cost management, present value of total cost is $51 million over 35 years. Table 11 summarizes present value total costs for the five management alternatives.

Table 11 Summary of LFA impacts over 35 years – by Management alternative

Total	Status Quo	Reduced Management	Least Cost	Least Sting	Eradicate LFA
PV Total Cost	6.1 billion	12.9 billion	51.26 million	944.18 million	561.63 million
Human stings	2255 million	3429 million	94.4 million	6.4 million	28.2 million
Pet stings	0.9 billion	1.9 billion	11 million	4 million	9 million

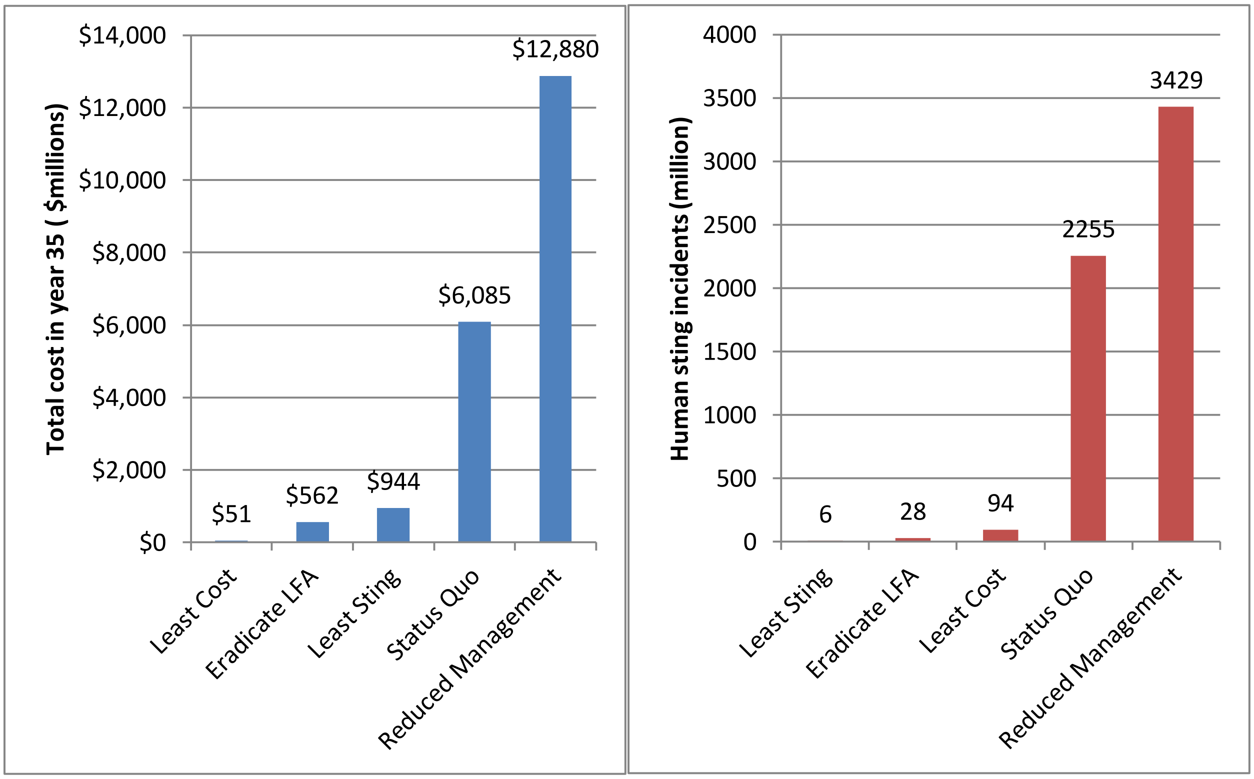


Figure 12 Summary of LFA impacts over 35years - by Management alternative

Sector analysis - LFA impacts by management alternative

Reduced management

Under **reduced management** in the coming 5 years, LFA will spread on the Big Island 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. Number of sting incidents is highest in the residential sector. In 35 years, the present value of total cost including management expenditures and economic damages from LFA is $12.9 billion. The total number of LFA sting incidents to children, adults and visitors over 35 years is 3.4 billion.

Status quo

Under **status quo management** in the coming 5 years, LFA will spread on the Big Island infesting 31%, 50%, 60%, 52% of the nursery, lodging, park, and school sectors. In 10 years, infestation will reach 42% and 54% in the nursery and lodging sectors. Costs 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 of total cost from LFA is $6.1 billion based on $5.536 billion management expenditures and $549 million in economic damages. Total number of LFA sting incidents to children, adults and visitor is 2.3 billion.

Least cost

Under **least cost management** in the coming 5 years, LFA infestations decrease to 5% and 24% in the lodging and school sectors, and are brought below 2.5% or lower in the nursery and lodging sector, and are suppressed to 1% or lower in all other sectors. Within 27 years, LFA are suppressed in all sectors. Under least cost management, LFA suppression is achieved with early mitigation treatment; prevention and detection in all infested sectors reduces infestation and slows the rate of spread. 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, present value of total cost is $51 million based on an estimated $40 million in management expenses and $11 million in damages. LFA sting incidents are 94 million.

Eradicate LFA

Under **eradicate LFA management** in the coming 5 years, LFA are suppressed in all sectors. Under eradicate LFA management, LFA suppression is achieved with aggressive mitigation treatment, prevention, and detection in all infested sectors. Prevention expenditures are largest in the park and residential sectors where initial infestation is highest. Detection and mitigation expenditures are greatest in the park sector where land area is largest. Over 35 years, present value of total cost is $562 million based on an estimated $555 million in management expenses and $7 million in damages. LFA sting incidents are 28 million.

Least sting incidents

Under **least sting incidents management** in the coming 5 years, LFA are suppressed in all sectors. Under least sting management, LFA suppression is achieved with rapid mitigation treatment, prevention, and detection in all infested sectors to eliminate LFA infestations and prevent new infestations. Detection expenditures are highest in the agriculture, other, and school sectors. Prevention expenditures are greatest in the lodging and park sectors. Over 35 years, present value of total cost is $944 million based on an estimated $939 million in management expenses and $5 million in damages. LFA sting incidents are 6 million.

Table 12 LFA infestation – by economic sector[a] (year 5, year 10, year suppressed)

	Sector	Status Quo	Reduced Management	Least Cost	Least Sting	Eradicate LFA
Year 5 infestation	Nursery	31.03%	53.22%	0.79%	0%	0.9%
	Agriculture	4.52%	4.56%	1.48%	0.18%	0.19%
	Lodging	50.01%	65.92%	5.47%	0%	0.13%
	Residence	11.13%	11.15%	0.00%	0%	0.05%
	Parks	60.20%	71.46%	0.35%	0%	1.14%
	Schools	52.50%	53.57%	24.22%	0%	0.1%
	Other	8.02%	8.05%	0.73%	0%	0.07%
	Total	**10.16%**	**10.48%**	**0.4%**	**0.01%**	**0.07%**
Year 10 infestation	Nursery	41.66%	57.49%	1.24%	0%	0.09%
	Agriculture	11.98%	12.35%	2.34%	0.14%	0.14%
	Lodging	53.66%	71.04%	2.9%	0%	0.1%
	Residence	23.08%	23.38%	0%	0%	0.06%
	Parks	56.72%	74.07%	0.02%	0%	0.9%
	Schools	44.59%	62.35%	26.76%	0%	0.2%
	Other	11.31%	11.52%	0.49%	0%	0.11%
	Total	**18.68%**	**19.22%**	**0.35%**	**0.01%**	**0.08**
Year LFA infestation is suppressed	Nursery	Not Suppressed	Not Suppressed	16	2	5
	Agriculture			14	1	1
	Lodging			27	1	4
	Residence			1	1	2
	Parks			3	1	8
	Schools			13	1	3
	Other			2	2	2
	Overall			**27**	**2**	**8**

[a] Based on number infested sites per sector, e.g. number of farms, number of parks, etc.

[b] Defined sustained infestation levels below 0.1%

Table 13 PV total cost and human sting incidents – by economic sector (over 35 years)

	Sector	Status Quo	Reduced Management	Least Cost	Least Sting	Eradicate LFA
PV total cost ($ million)	Nursery	$76.06	$161.57[a]	$3.13	$7.59[b, c]	$1.68
	Agriculture	$1,091.44	$2,721.77[a]	$11.46	$106.52[b]	$12.42
	Lodging	$301.38	$550.42[a]	$15.47	$123.40[b, c]	$22.60
	Residence	$324.75	$546.99[a]	$9.20	$8.79	$5.39[b, c]
	Parks	$2,996.97	$5,989.61[a]	$1.47	$474.64[c]	$350.18[b]
	Schools	$1,058.29	$2,449.66[a]	$6.92	$129.17[b]	$163.95
	Other	$236.30	$460.04[a]	$3.62	$94.07[b]	$5.41
	Total	$6,085.20	$12,880.05[a]	$51.27	$944.18[b, c]	$561.63
Human sting incidents (million)	Nursery	16.1	24	0.5	0.2	0.6
	Agriculture	7.0	12	0.3	0.0	0.0
	Lodging	372.1	503	23.2	0.2	5.6
	Residence	766.8	1329	4.6	4.1	6.9
	Parks	485.8	661	1.6	0.4	10.2
	Schools	457.0	677	60.8	0.4	3.1
	Other	150.2	223	3.3	1.1	1.8
	Total	**2255.0**	**3428.6**	**94.4**	**6.4**	**28.2**

[a] Management alternative with the highest mitigation expenditures per site.

[b] Management alternative with the highest detection expenditure per site.

[c] Management alternative with the highest prevention expenditure per site.

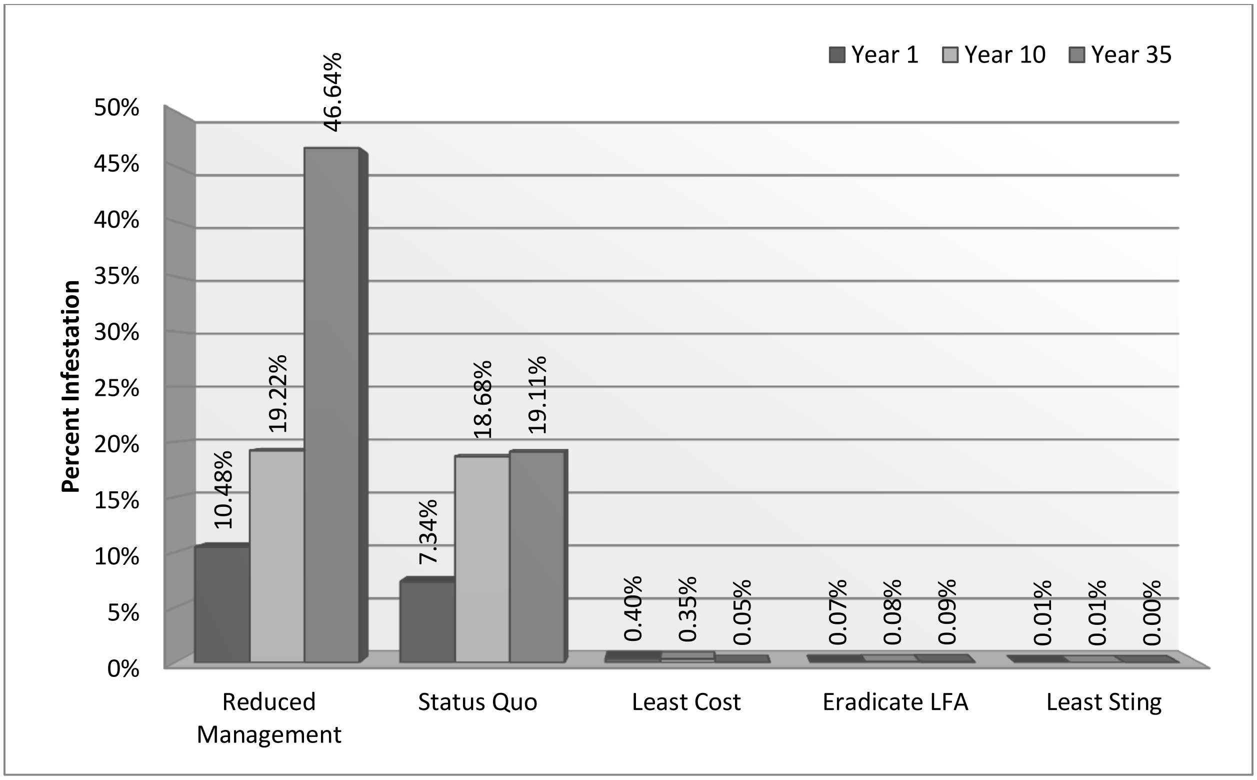


Figure 13 LFA infestation on the Big Island – all economic sectors

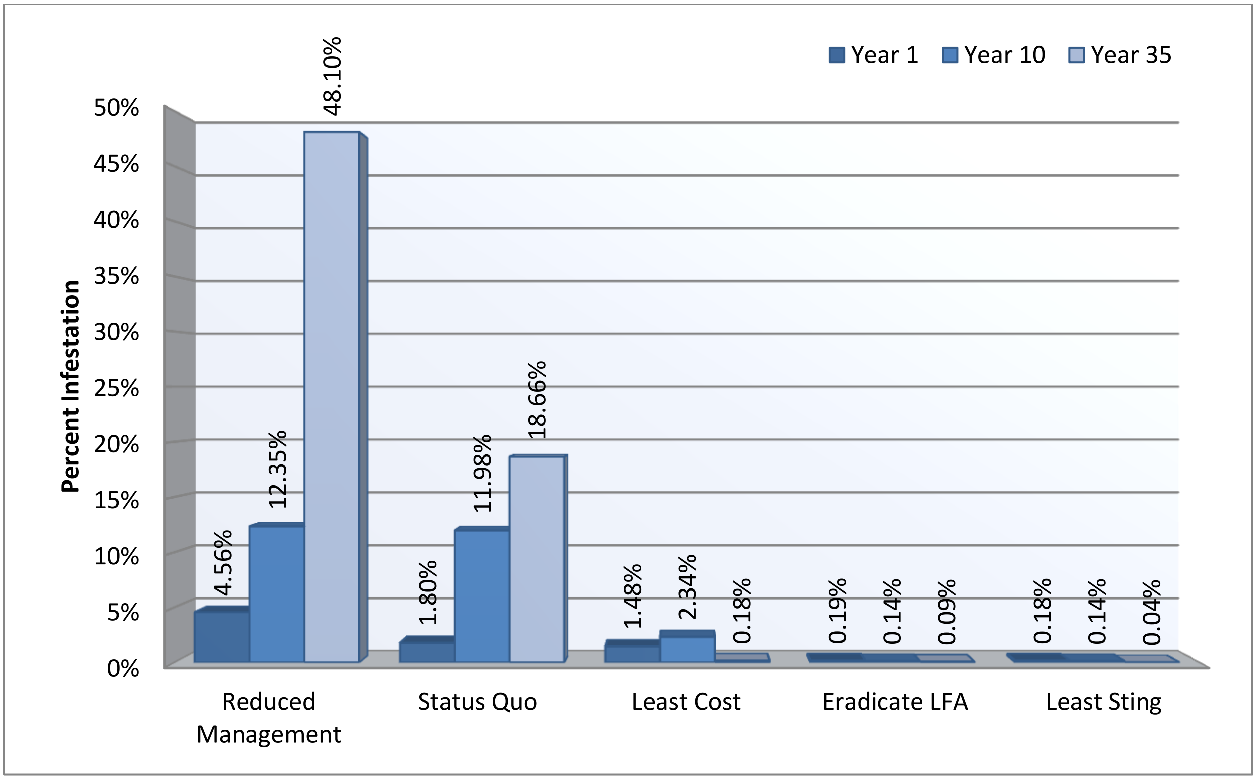


Figure 14 LFA infestation in the Agricultural sector

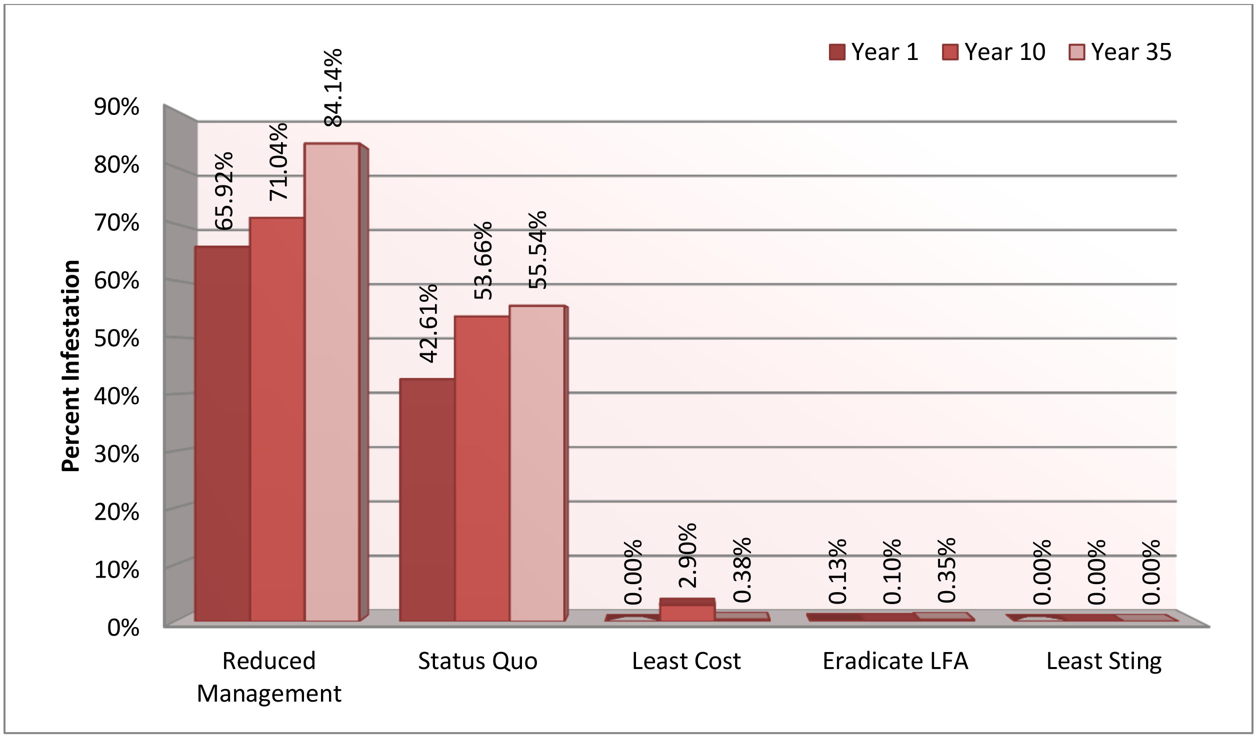


Figure 15 LFA infestation in the Lodging sector

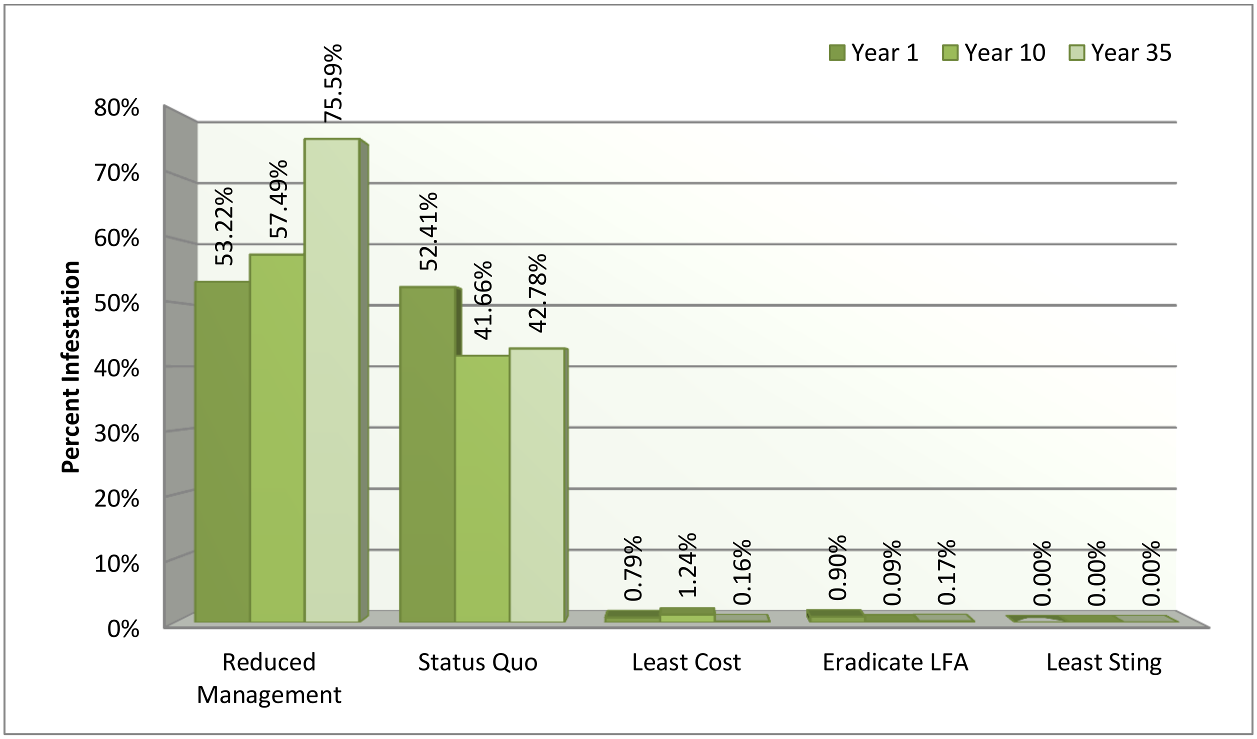


Figure 16 LFA infestation in the Nursery sector

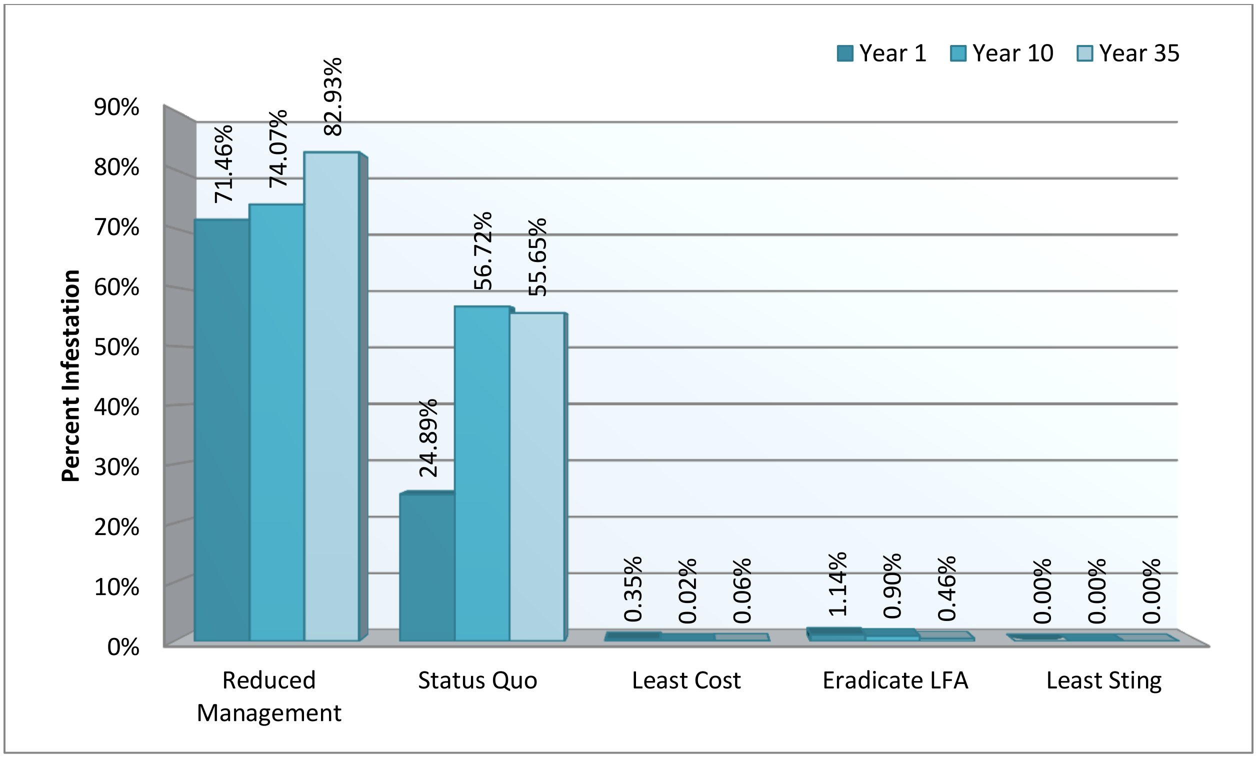


Figure 17 LFA infestation in the Parks sector

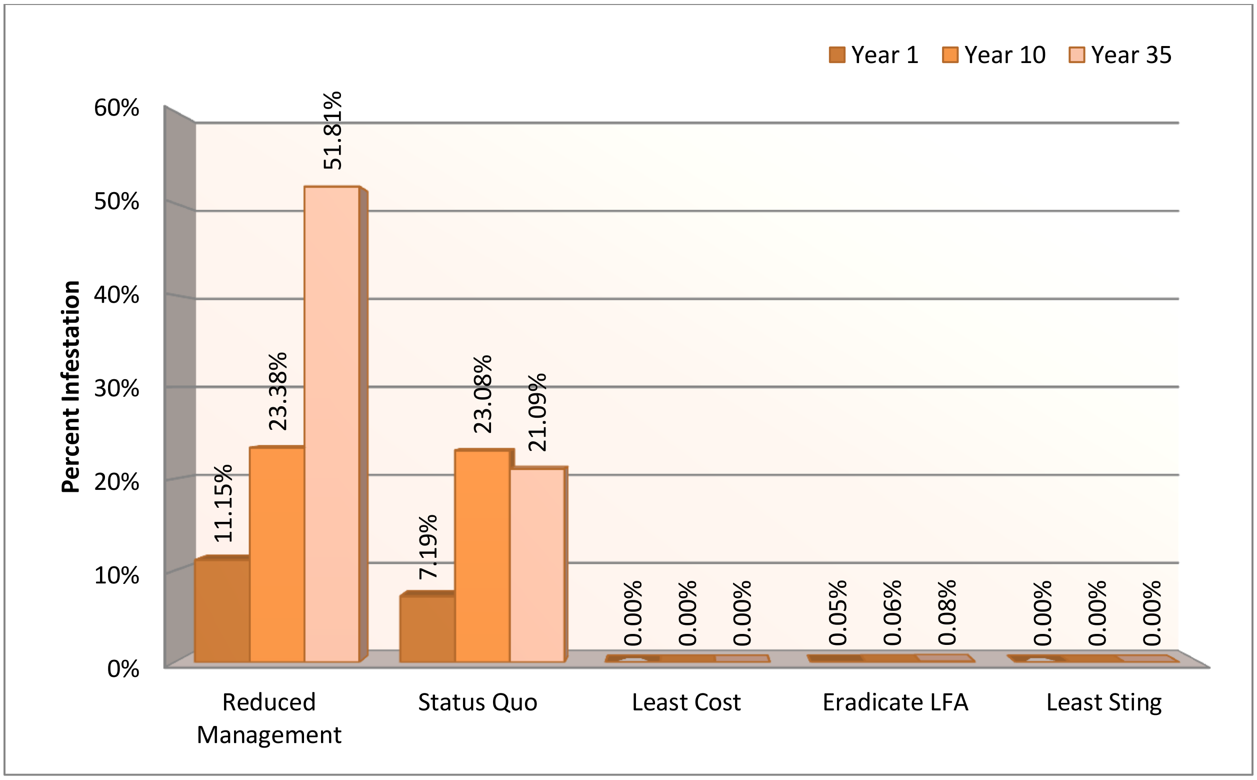


Figure 18 LFA infestation in the Residential sector

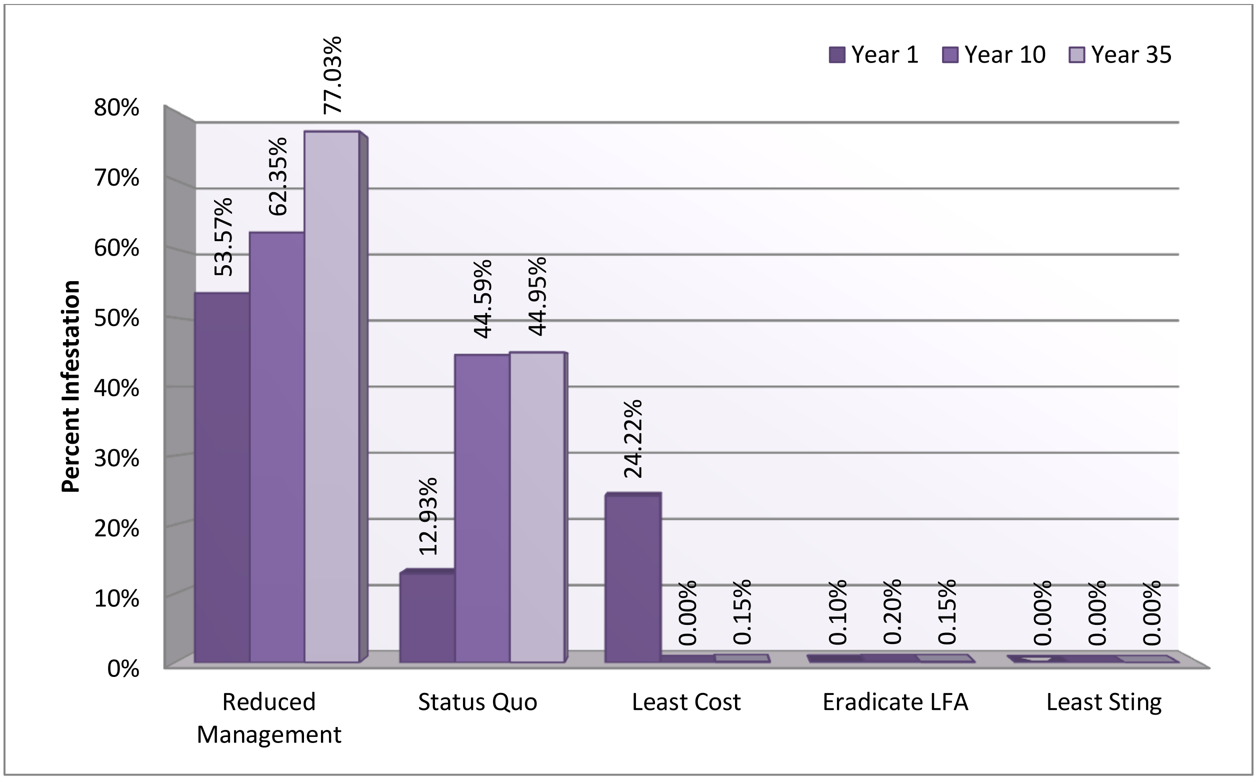


Figure 19 LFA infestation in the School sector

Additional results can be found in Appendix A.

Comparison to current management

Over 35 years, current (status quo) management will lead to \$6.1 billion in LFA management costs and damages and 2.3 billion human sting incidents. Reduced management (below status quo) lowers early public expenditure which leads to *higher* sector expenditures and damages \$6.8 billion and 52% more human sting incidents than the status quo. Least cost management increases early management effort to *lower* long run costs by \$6.0 billion and reduce human sting incidents by 96% compared to the status quo. Eradicate LFA management increases early management effort where LFA infestations are worst to reduce infestations and spread thereby lowering long run costs by \$5.5 billion and reducing human sting incidents by 2.23 billion compared to the status quo. Least sting management increases early management effort in the most populated sectors, which leads to a reduction in long run of \$5.1 billion and a decrease of 2.25 billion human sting incidents compared to the status quo. Total and sector results comparing management alternatives to the status quo appear in Table 14 and Table 15.

Table 14 LFA impacts by management alternative compared to the Status Quo (over 35 years)

	Sector	Reduced Management	Least Cost	Least Sting	Eradicate LFA
PV total management costs and damages $ million	Nursery	$85.50	-$72.93	-$68.47	-$74.38
	Agriculture	$1,630.33	-$1,079.98	-$984.92	-$1,079.02
	Lodging	$249.04	-$285.91	-$177.98	-$278.78
	Residence	$222.24	-$315.55	-$315.96	-$319.36
	Parks	$2,992.64	-$2,995.50	-$2,522.33	-$2,646.79
	Schools	$1,391.37	-$1,051.37	-$929.12	-$894.35
	Other	$223.74	-$232.68	-$142.23	-$230.89
	Total	$6,794.85	-$6,033.93	-$5,141.02	-$5,523.57
Human sting incidents million	Nursery	8.00	-15.54	-15.84	-15.53
	Agriculture	4.52	-6.78	-6.99	-6.99
	Lodging	131.04	-348.92	-371.95	-366.50
	Residence	562.08	-762.13	-762.72	-759.88
	Parks	175.02	-484.13	-485.37	-475.55
	Schools	219.80	-396.21	-456.58	-453.91
	Other	73.20	-146.82	-149.08	-148.39
	Total	1,173.67	-2,160.53	-2,248.52	-2,226.75

Table 15 LFA impacts by management alternative compared to the Status Quo (% difference) over 35 years

	Sector	Reduced Management	Least Cost	Least Sting	Eradicate LFA
PV Total management costs and damages	Nursery	112%	-96%	-90%	-98%
	Agriculture	149%	-99%	-90%	-99%
	Lodging	83%	-95%	-59%	-93%
	Residence	68%	-97%	-97%	-98%
	Parks	100%	-100%	-84%	-88%
	Schools	131%	-99%	-88%	-85%
	Other	95%	-98%	-60%	-98%
	Total	112%	-99%	-84%	-91%
Human sting incidents	Nursery	50%	-97%	-98%	-97%
	Agriculture	64%	-96%	-99%	-99%
	Lodging	35%	-94%	-100%	-98%
	Residence	73%	-99%	-99%	-99%
	Parks	36%	-100%	-100%	-98%
	Schools	48%	-87%	-100%	-99%
	Other	49%	-98%	-99%	-99%
	Total	52%	-96%	-100%	-99%

Net benefit analysis – 10 years of management

Under Least Cost management, early spending on prevention, detection, and control totaling \$8.23 million will generate present value of cost savings of \$762 million over 10 years for a benefit-cost ratio of 93:1. Compared to Status Quo management, Least Cost management will result in 291 million fewer human sting incidences and 102 million fewer pet sting incidences over 10 years, equivalent to 2.4 fewer sting incidences per person per week and 0.9 fewer sting incidences per pet per week. Given the current 128,899 infested acres, average management expenditure is \$309 an acre, significantly lower than the amount spent eradicating LFA in the Galapagos, \$4,890[43] per acre. Results are illustrated in Figure 22 and Figure 23.

Under least LFA sting incidences management, early spending on prevention, detection, and control totaling \$890 million will generate present value of cost savings of \$744 million over 10 years for a benefit-cost ratio of 0.8:1. Compared to status quo management, least sting incidences management will result in 361 million fewer human sting incidences and 102 million fewer pet sting incidences over 10 years, equivalent to 3.0 fewer sting incidences per person per week and 1.0 fewer sting incidences per pet per week. Given the current infested area of 128,899 acres, average management expenditure is \$5,565 per acre in the first year and \$7,288 per acre over 35 years, comparable to the expenditures for eradicating LFA in the Galapagos, \$4,890 per acre (Causton, Sevilla, & Porter, 2005). Results are illustrated in Figure 24 and Figure 25.

Under eradicate LFA management, early spending on prevention, detection, and control totaling a \$495 million will generate present value of cost savings of \$749 million over 10 years for a benefit-cost ratio of 1.5:1. Compared to status quo management, eradication management will result in 347 million fewer human sting incidences and 102 million fewer pet sting incidences over 10 years, equivalent to 2.9 fewer sting incidences per person per week and 0.9 fewer sting incidences per pet per week. Results are illustrated in Figure 26 and Figure 27.

---

[43] The 2005 Causton, Sevilla & Porter figure of \$4,100 has been adjusted for inflation.

Reduced management compared to the status quo

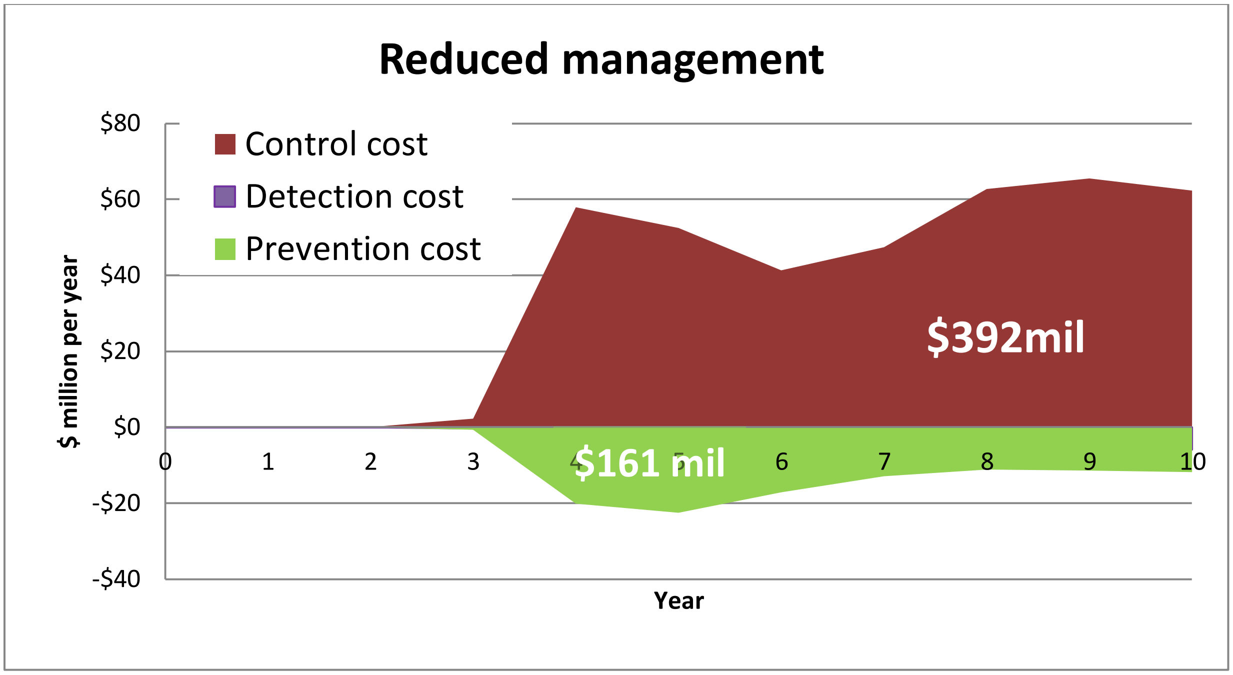


Figure 20 Cost comparison for reduced management compared to the status quo – 10 years

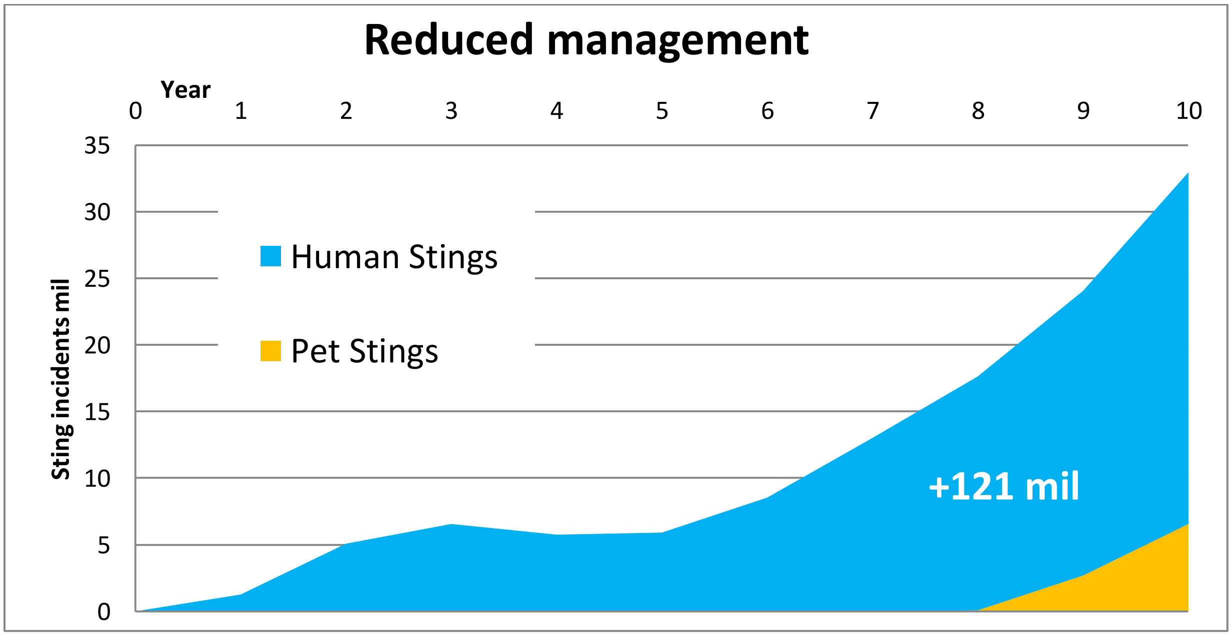


Figure 21 Sting comparison for reduced management compared to the status quo – 10 years

Least cost management compared to the status quo

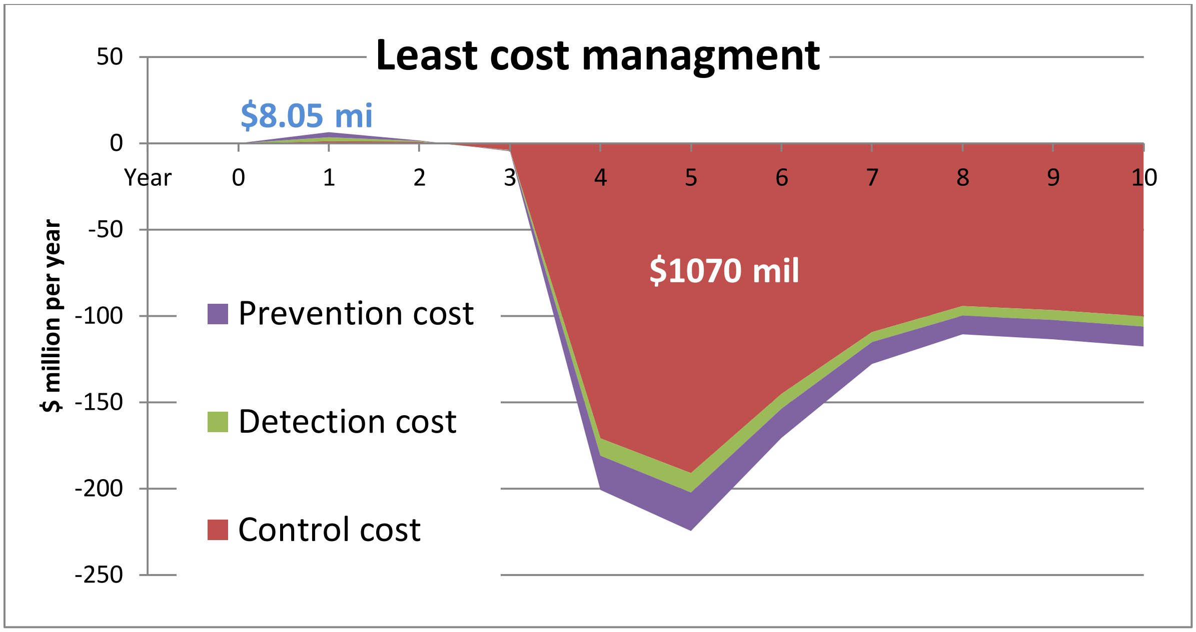


Figure 22 Cost comparison for least cost management compared to the status quo – 10 years

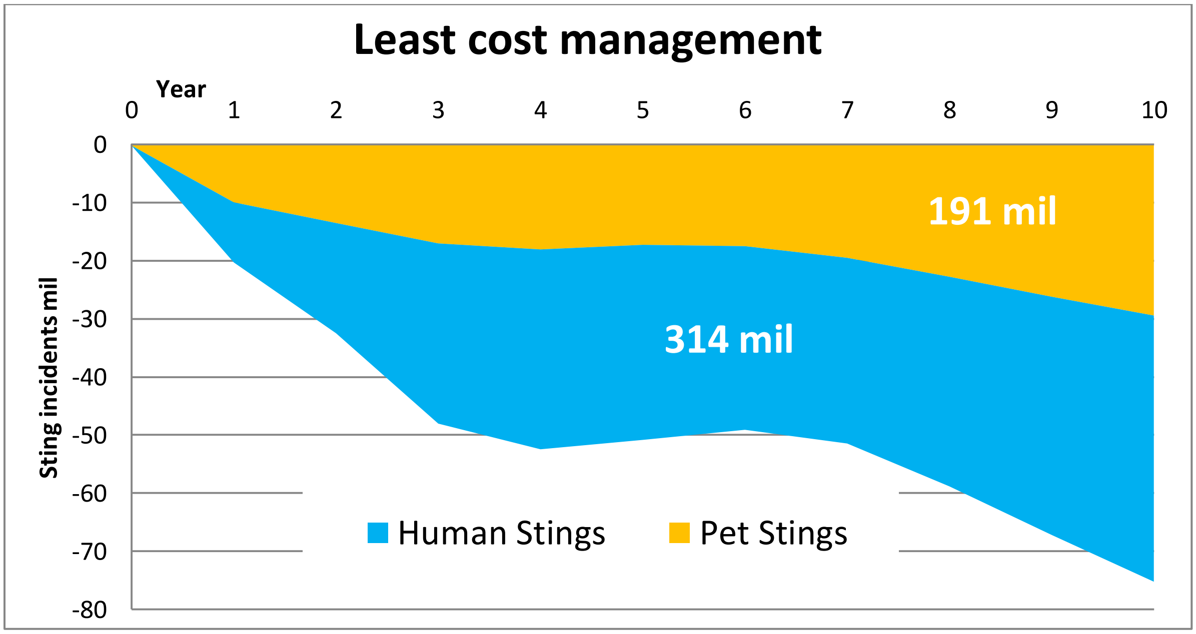


Figure 23 Sting comparison for least cost management compared to the status quo – 10 years

Least sting incidents management compared to the status quo

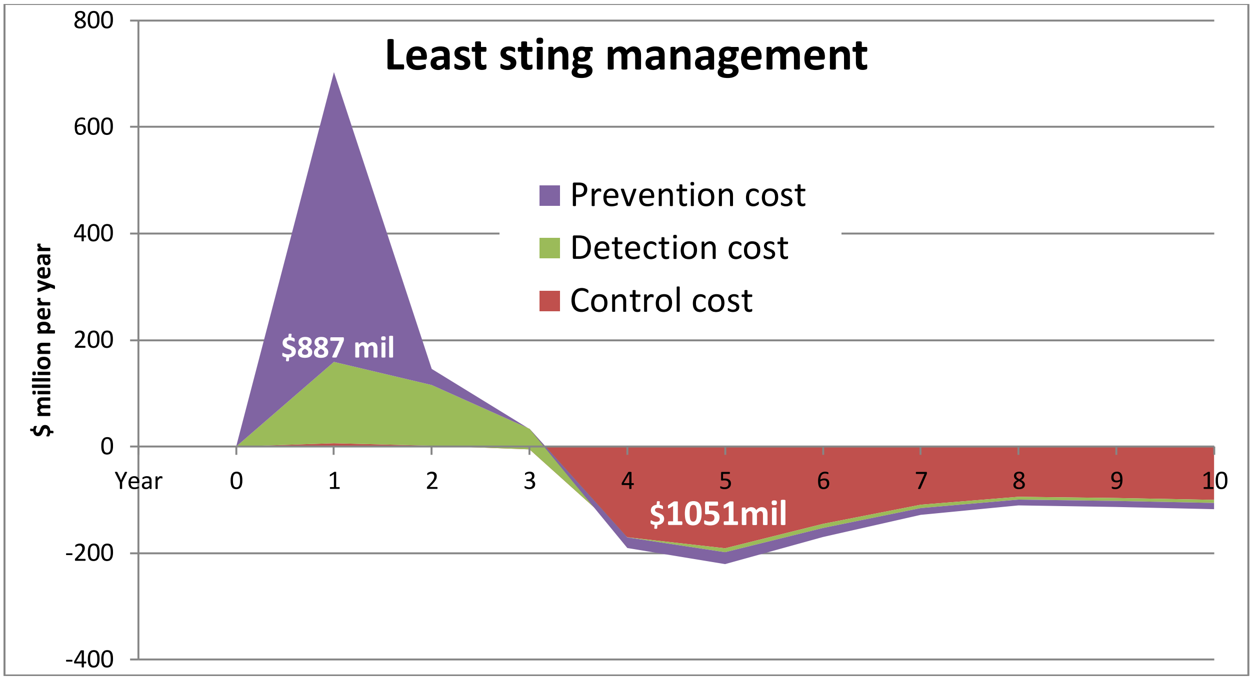


Figure 24 Cost comparison for least sting management compared to the status quo – 10 years

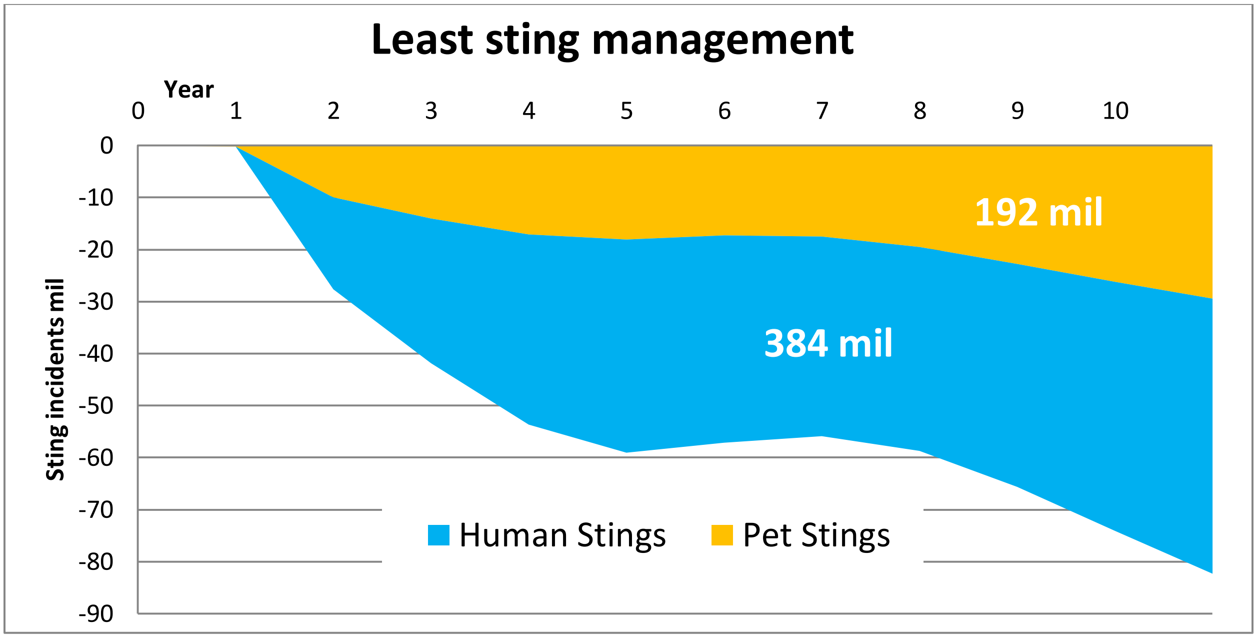


Figure 25 Sting comparison for least sting management compared to the status quo – 10 years

Eradicate LFA management compared to the status quo

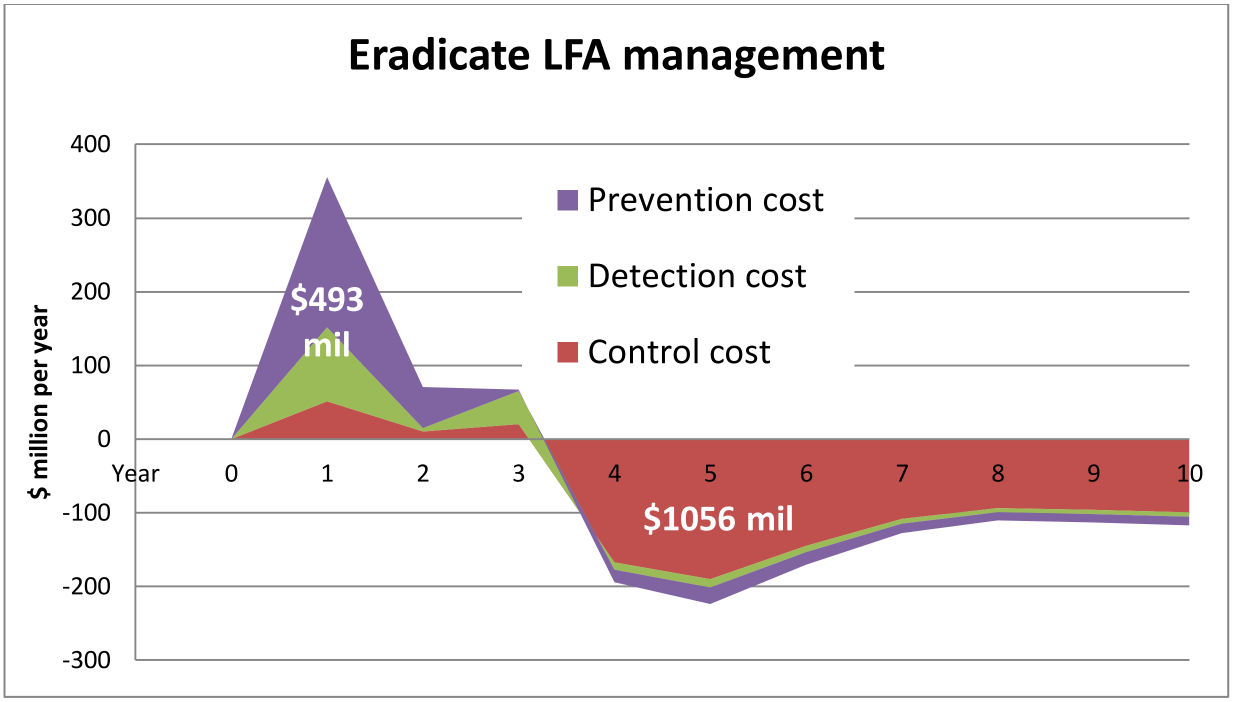


Figure 26 Cost comparison for eradicate LFA management compared to the status quo – 10 years

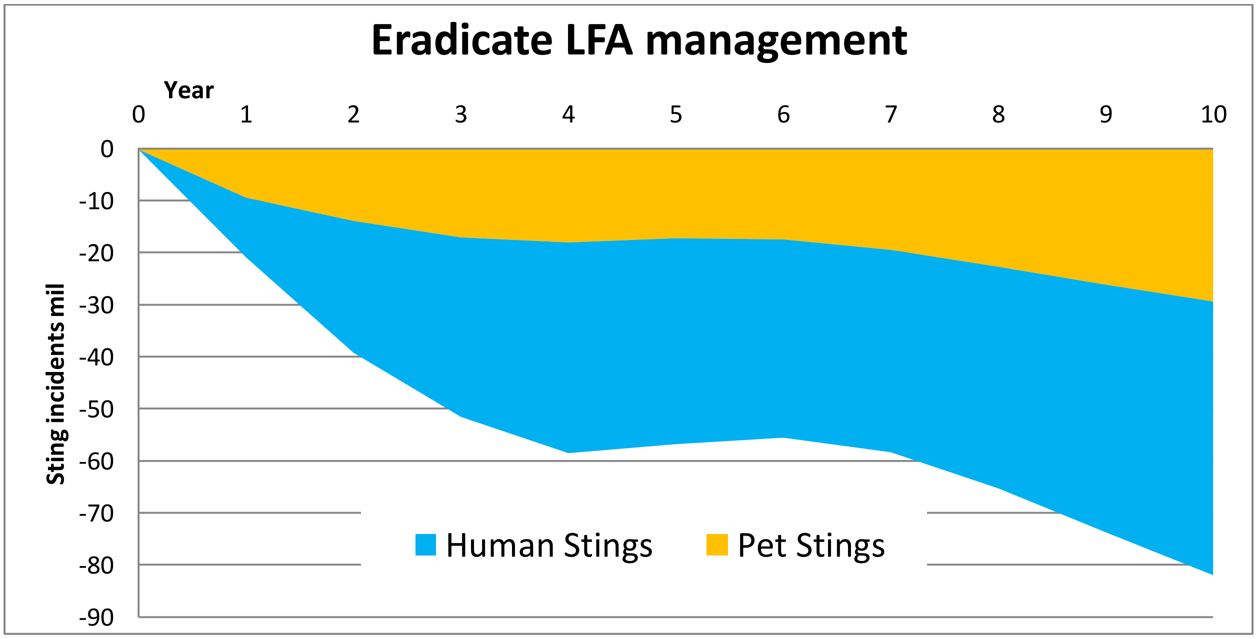


Figure 27 Sting comparison for eradicate LFA management compared to the status quo – 10 years

Sensitivity analysis – Eight key parameters

Description

Our model optimization results indicate that there is clear room for improvement in management of LFA on the Big Island. Increased expenditures on prevention, detection, and mitigation in all sectors would reduce LFA infestations, reduce economic damages, lower future mitigation costs, and reduce LFA sting incidences. To examine the robustness of the model results, we conducted sensitivity analyses on the model assumptions and empirical parameters. We tested LFA spread rate, growth rate, and establishment rate. We tested management material and labor costs, we monetized losses due to sting incidents, and we estimated economic losses from ecosystem damages. We tested management effectiveness for mitigation treatment, prevention, and detection.

Empirical findings

In our baseline model we assume that under status quo management, LFA will inundate the Big Island in 13 years. If LFA is expected to spread in 7 years, then under status quo management PV total cost will be $8.2 billion, under least cost management PV total cost will be $51 million. If LFA is expected to spread across the Big Island in 20 years, then under status quo management PV total cost will be $1.58 billion, under least cost management PV total cost will be $29.7 million. Results appear as Sensitivity tests No. 1-i and 1-ii in Table 16. From these findings we conclude that additional LFA management effort beyond the status quo is economically warranted if LFA is expected to inundate the island quickly (in seven years) or slowly (in 20 years).

In our baseline model we did not attach a damage value to human sting incidents. If each human sting incident causes an average $5 worth of damage then under status quo management, PV total cost will be $13.7 billion, under least cost management PV total cost will be $38.6 million. If each human sting incident causes an average of $25 worth of damage, then under status quo management PV total cost will be $44.4 billion, under least cost management PV total cost will be $141.6 million. Results appear as Sensitivity tests No. 3-i and 3-ii in Table 16. From these findings we conclude that additional LFA management effort beyond the status quo is warranted even if the average damage per human sting incident is small.

In our baseline model we did not quantify economic damages from lost ecosystem services. If LFA infestations generate ecosystem service losses of $25 per acre, then under status quo management PV total cost will be $6.08 billion, under least cost management PV total cost will be $533.8 million. If LFA infestations generate ecosystem service losses of $250 per acre, then under status quo management PV total cost will be $6.09 billion, under least cost management PV total cost will be $30.7 million. Results appear as Sensitivity tests No. 4-i and 4-ii in Table 16. From these findings, we conclude that additional LFA management effort beyond the status quo is warranted even if ecosystem service losses are small.

Table 16 Sensitivity results – Comparison of 3 management alternatives

No.	**Sensitivity test**				**Annual human sting incidents***			**PV Total Cost**		
	Parameter	Units	Base Value	Test value	Status quo	Least cost	Least sting	Status Quo	Least cost	Least sting
1			**Base model**		**74**	**1.64**	**0.59**	**$6,085**	**$30.73**	**$940.60**
1-i	Growth and spread	Year**	13	7	83	0.49	0.07	$8,209	$51.26	$944.18
1-ii				20	18	1.55	0.54	$1,584	$29.73	$940.38
2-i	Management cost	$ per acre per day	$15	$7.50	74	1.64	0.59	$6,085	$31.70	$644.78
2-ii				$30	74	1.64	0.59	$6,085	$26.61	$1,532.24
3-i	Damage, sting incidents	$ per incident	$0	$5.00	74	1.33	0.59	$13,758	$38.61	$957.86
3-ii				$25	74	0.02	0.59	$44,448	$141.69	$1,026.90
4-i	Damage, ecosystem	$ per acre in PARKS	$0	$25.00	74	1.64	0.59	$6,086	$533.88	$940.60
4-ii				$250	74	1.64	0.59	$6,095	$30.70	$940.64
5-i	Establishment rate	%	10%	5%	74	1.64	0.59	$6,085	$30.83	$940.60
5-ii				1%	74	1.64	0.59	$6,085	$30.73	$940.60
6-i	Discount rate	%	2%	4%	74	1.64	0.59	$4,282	$30.73	$914.90
6-ii				8%	74	1.64	0.59	$2,354	$28.25	$869.01
7-i	Mitigation effectiveness	% per application	40%	60%	69	1.52	0.53	$5,196	$24.02	$937.42
7-ii				80%	66	1.51	0.32	$4,904	$21.96	$936.81
8-i	Detection success	%	25%	50%	74	1.63	0.50	$6,085	$30.37	$940.11
8-ii				99%	74	1.46	0.49	$6,085	$30.12	$940.04

*In year 35
**Year that LFA infestation is island-wide

Over a range of plausible parameter values, the results from the sensitivity analysis indicate that the model results are robust and that increased effort in prevention, detection, and mitigation treatment are warranted to reduce future costs, damages, and sting incidents.

More details from the sensitivity analysis appear in Appendix B.

Stochastic analysis – Five key parameters

Description

Spread, growth, and establishment of LFA over time and space is random. Experts have not had much success predicting where new infestations will occur. We model spread, growth, and establishment of LFA as random processes then examine the influence on optimal management.

We modeled stochastic processes using Risk Solver Platform. We assigned value p the probability of survival and n the number of infested sites to the binomial distribution $B(n, p)$ so the number of sites with a new infestation $N_i^{introduced}$ is a random variable with probability of survival $p = \lambda_j^{survival}$, at number of sites n = $N_{i,t}^{in}$, thus $N_i^{introduced} = B\left(N_{i,t}^{in}, \lambda_j^{survival}\right)$.

Table 17 Stochastic parameters

Name	Description	Range
$\lambda_i^{invasion}$	Proportion of new reproduction in sector i that spreads	$0.01 \leq \lambda_i^{invasion} \leq 0.20$
$\lambda_j^{survival}$	Proportion of new propagules that survive	$0.01 \leq \lambda_j^{survival} \leq 0.115$
$\lambda_{i,t}^{detect}$	Proportion of new propagules that are detected per unit of detection effort	$0.35 \leq \lambda_{i,t}^{detect} \leq 0.95$
$\lambda_{i,t}^{mitigate}$	Proportion of treated sites at which LFA are completely destroyed per unit of mitigation effort	$0.40 \leq \lambda_{i,t}^{mitigate} < 1$
$\lambda_{i,t}^{prevent}$	Proportion of sites at which LFA is deterred per unit of prevention effort	$0.35 \leq \lambda_{i,t}^{prevent} \leq 0.95$

The stochastic analysis includes two ranges: a **90% confidence** range derived from the joint distribution of the stochastic parameters; and a **management effectiveness** range based on the upper and lower bounds of the stochastic parameters. High management effectiveness is based on a low spread rate $\lambda_i^{invasion} = 0.01$, a high survival rate $\lambda_i^{survival} = 0.01$, a high detection rate $\lambda_{i,t}^{detect} = 0.95$, a high mitigation control rate $\lambda_{i,t}^{mitigate} = 1$, and a high prevention success rate $\lambda_{i,t}^{prevent} = 0.95$. Low management effectiveness is based on a high spread rate $\lambda_i^{invasion} = 0.20$ a high survival rate $\lambda_i^{survival} = 0.115$, a low detection rate $\lambda_{i,t}^{detect} = 0.35$, a low mitigation control rate $\lambda_{i,t}^{mitigate} = 0.40$, and a low prevention success rate $\lambda_{i,t}^{prevent} = 0.35$.

Empirical findings

Status quo

Projected infestation with low management effectiveness is higher than projected infestation with stochastic parameters within the 90% CI. Projected infestation within the 90% CI is higher than projected infestation with deterministic parameters. Projected infestation with high management effectiveness is lower than projected infestation with deterministic parameters, and furthermore decreasing over time falling below 20% infestation in the long run. Stochastic model results for status quo management are shown in Figure 28.

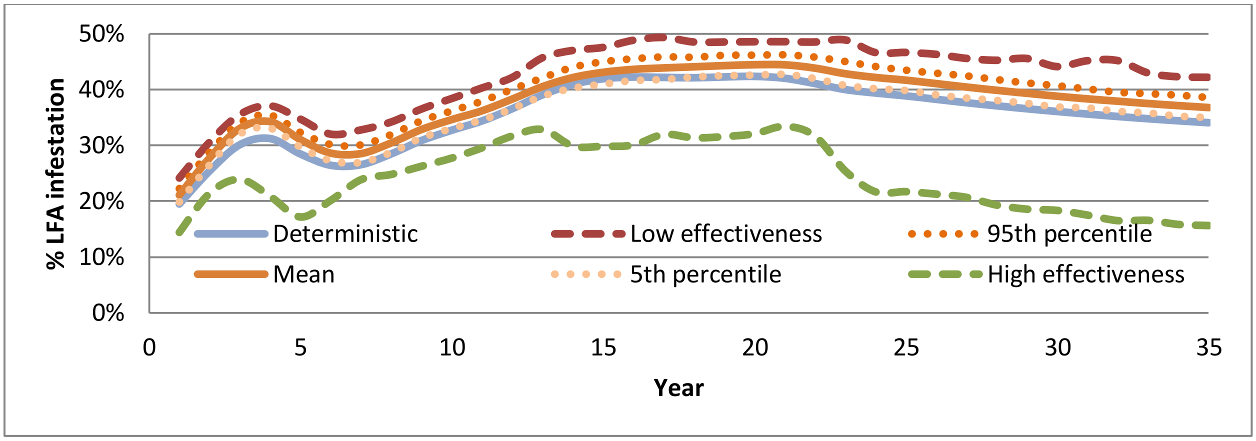


Figure 28 Stochastic Status Quo – LFA infestation

PV cumulative cost with low management effectiveness is higher than PV cumulative cost with stochastic parameters within the 90% CI. PV cumulative cost within the 90% CI is higher than PV cumulative cost with deterministic parameters. PV cumulative cost with high management effectiveness is lower than PV cumulative cost with deterministic parameters. Stochastic model results for status quo management are shown in Figure 28.

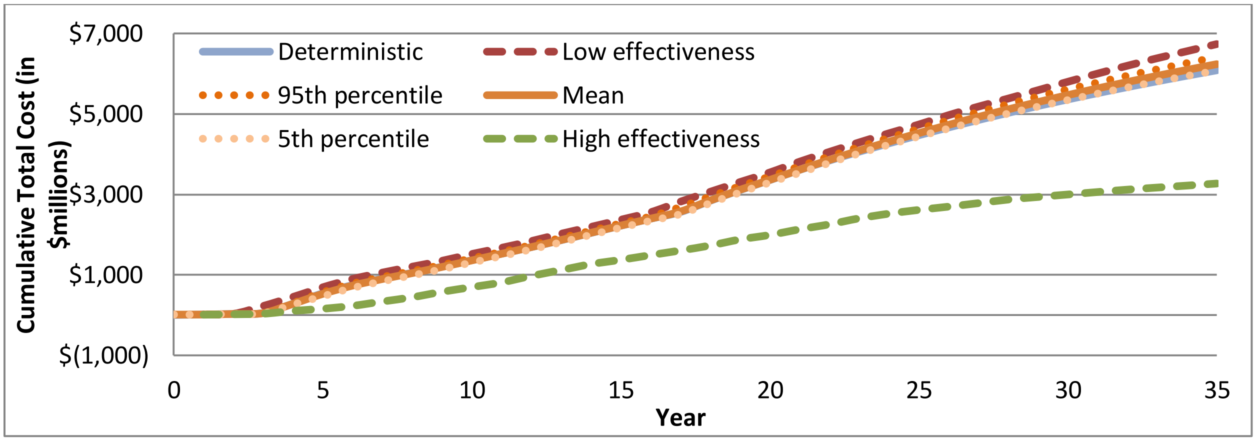


Figure 29 Stochastic Status Quo – Cumulative total cost

Least cost

Projected infestation with low management effectiveness is higher than projected infestation with stochastic parameters within the 90% CI. Projected infestation within the 90% CI encompasses projected infestation with deterministic parameters.[44] Projected infestation with high management effectiveness is lower than projected infestation with deterministic parameters. Stochastic model results for least cost management are shown in Figure 30.

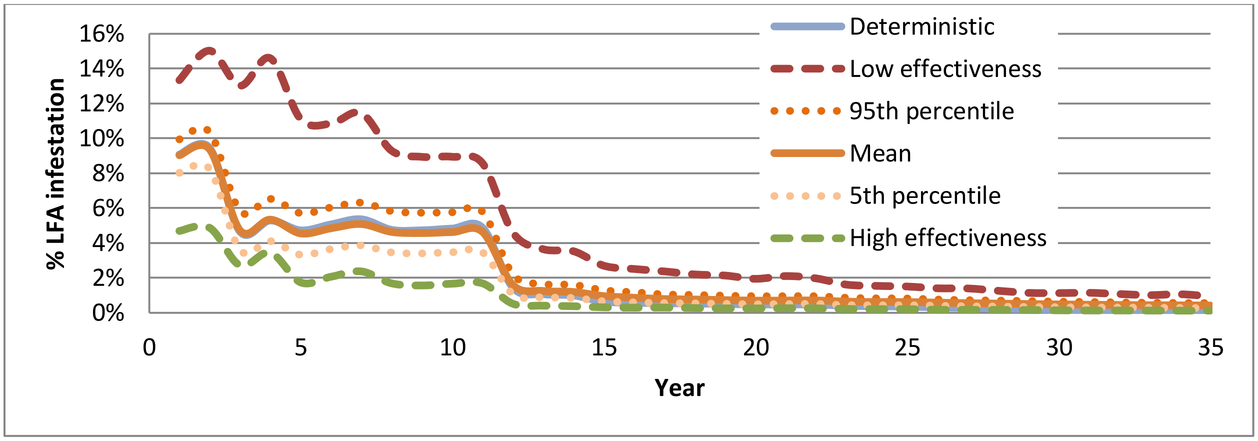
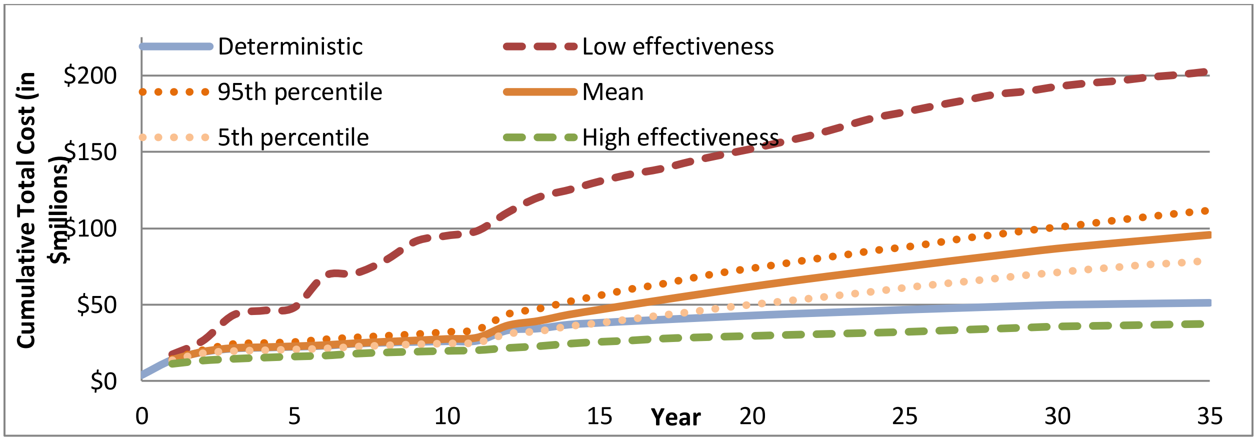


Figure 30 Stochastic Least Cost – LFA infestation

PV cumulative cost with low management effectiveness is higher than PV cumulative cost with stochastic parameters within the 90% CI. PV cumulative cost within the 90% CI is higher than PV cumulative cost with deterministic parameters. PV cumulative cost with high management effectiveness is lower than PV cumulative cost with deterministic parameters. Stochastic model results for least cost management are shown in Figure 30.



---

[44] The probability distributions used in the stochastic model are relatively narrow. Our model includes a large *n* number infested sites which decreases the coefficient of variation. Large *p* probability of success also narrows the distribution.

Figure 31 Stochastic Least Cost – Cumulative total cost overtime

Probability of success (and failure) due to random events

The probability that LFA infestation will fall below current (year 2012) infestation is 0% under status quo management and greater than 99% under least cost management after year 10. The probability that LFA infestation will rise above the current (year 2012) infestation is 100% under status quo management and less than 1% under least cost management after year 10.

The probability that society will be worse-off due to stochastic events for implementing least cost management rather than retaining status quo management is approximately zero -- the stochastic analysis shows that even under extreme events, the probability that least cost management will yield higher LFA infestation or higher cumulative total costs than status quo management is 0%. Results are displayed in Table 18.

Table 18 Probability values for extreme events

Event	Management type	Probability of occurrence		
		Year 1	Year 10	Year 35
Current infestation is less than the initial infestation	Least Cost	0.0%	99.8%	100.0%
	Status Quo	0.0%	0.0%	0.0%
Infestation under Least Cost management is greater than infestation under Status Quo management	Both	0%	0%	0%
Cumulative total cost under Least cost management is greater than cumulative total cost under Status Quo management	Both	0%	0%	0%

Multiple objective analysis – Two objectives

Description

If more than one objective is desirable, as is the case with LFA, it may be worthwhile to choose management alternatives to optimize multiple objectives. To this end, we applied the bioeconomic model to conduct a Pareto efficiency analysis. Results from the analysis provide information on the range of efficient management outcomes and the tradeoffs between total costs and total sting incidents. A Pareto outcome is **efficient** meaning it cannot be improved on, that is, a change in management can be used to reduce total sting incidents but at higher total cost or a change in management can reduce total cost but only with an increase in total sting incidents. An outcome is termed **inefficient** if a change in management can lead to an increase in total cost at the same level of sting incidents, or an increase in sting incidents at the same level of total cost. An outcome is termed **unattainable** if it cannot be achieved with any combination of existing management alternatives.

The Pareto efficient frontier is illustrated with a blue line in Figure 32 depicting the locus of outcome pairs (total sting incidents, total cost) that are **efficient**. The blue region indicates the set of outcomes that are **inefficient**. The green region indicates the set of outcomes that are **unattainable**.

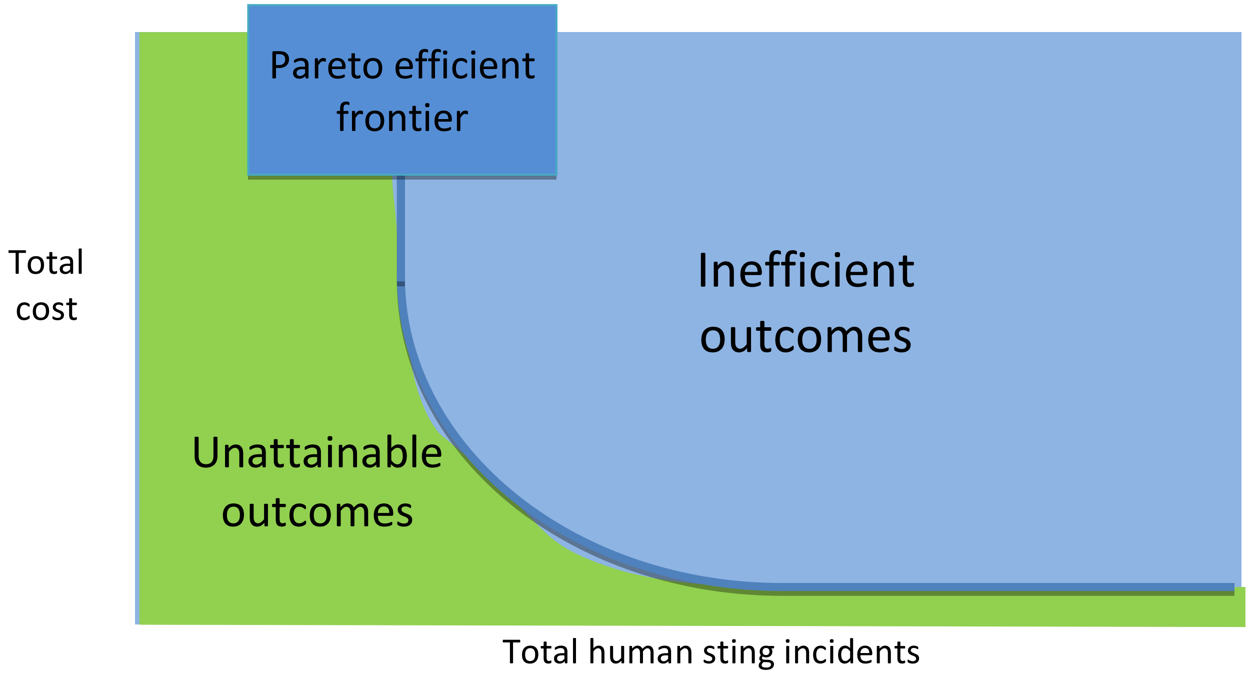


Figure 32 Illustration of Pareto efficient frontier

Empirical findings

The least cost management approach yields a PV total cost of $51 million and 94 million human sting incidents. Increasing management effort to PV total cost of $91 million reduces human sting incidents to 73 million where marginal cost is $2 per human sting incident avoided. If damage per sting incident is greater than $2, then the additional $40 million in management is worthwhile. If damage per human sting incident is $5 or more, then management effort that would reduce human sting incidents to 17 million resulting in PV total cost of $159 million would be deemed worthwhile. Numerical results from the multi-objective analysis are displayed in Table 19.

Table 19 Marginal cost per sting incident avoided on the efficient frontier

PV Total Cost	Sting incidents	Marginal cost per avoided sting incident*
$ 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

*This is calculated as a change from previous point (i.e., row above).

Least cost management leads to an **efficient outcome** by design, PV of total cost is minimized at $51 million and correspondingly, human stings incidents are reduced to 94 million.

Least sting management also leads to an **efficient outcome** by design, sting incidents are minimized at 6 million and PV of total cost is $944 million. The marginal cost per avoided human sting incident is estimated to be $306.

Status quo management leads to an **inefficient outcome** with PV of total cost of $6.08 billion and 2.3 billion human stings incidents.

Reduced management also leads to an **inefficient outcome** with PV of total cost of $12.9 billion and 3.4 billion human stings incidents.

Efficient outcomes ranging from $2 to $306 per avoided sting incidents are illustrated in Figure 33. At higher total cost levels, society may prefer to allow the sting incidents to occur rather than pay for additional management.

Additional detail and results from the multiple objective analysis appears in Appendix C.

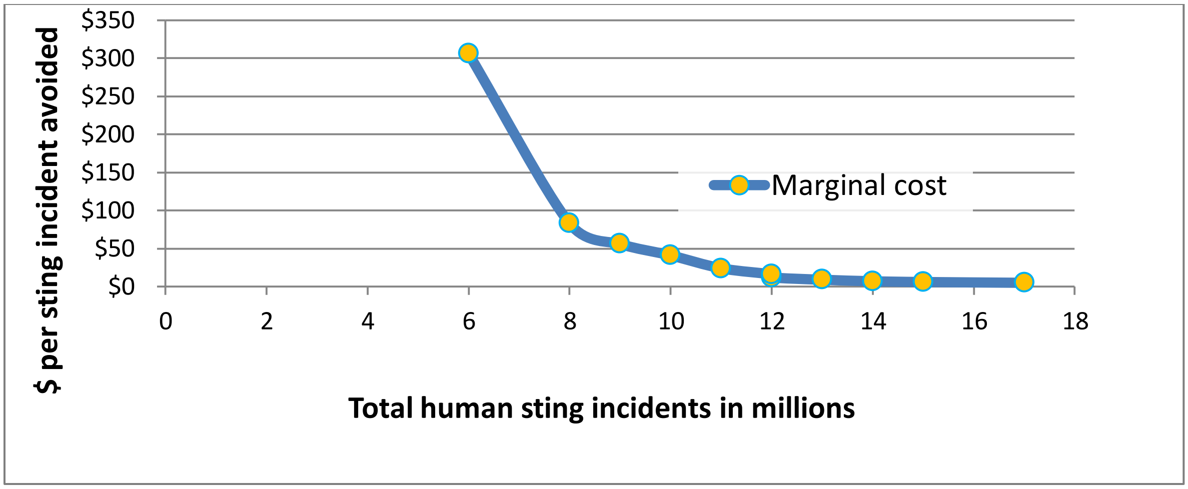


Figure 33 Marginal cost per avoided human sting incident

Conclusion

LFA was introduced to Hilo in 1997. By the time LFA was discovered in 1999 it had already spread to 13 (known) locations. Following three years of active effort to stop LFA from spreading, by 2002 LFA were found at 22 (known) locations. Eleven years later in 2013 we estimate LFA has spread to over 4,000 locations on the Big Island.

Current LFA management on the Big Island includes ant identification, response, public information and assistance for treating LFA, technology development, public awareness and education. Findings from study indicate that while current efforts have slowed LFA spread they will not be sufficient to prevent LFA from inundating the Big Island.

We developed a bioeconomic model to project LFA spread, economic and social impacts, and potential for management to control LFA and mitigate impacts. We specified seven economic sectors: nursery and floriculture, lodging, residents, agriculture, parks, schools, and all other to characterize impacts, model transport mechanisms, and allow for disaggregate management decisions. We employed simulation and optimization methodologies to examine a range of management alternatives.

Results indicate that increased LFA management effort is economically warranted. Over 35 years, increased management effort would yield net benefits up to $5 billion in cost savings compared to the status quo management plus 2.1 billion fewer human sting incidents. Conversely, if funding for LFA public programs are cut, the Big Island will suffer an additional $6.8 billion in PV total cost and 1.1 billion more human sting incidents over 35 years.

This study made use of the best information available to parameterize the model however, the parameters are not perfect. We conducted a sensitivity analysis to test alternate plausible parameter values. Results from the sensitivity analysis indicate that our conclusions are robust - increased management effort in the form of prevention, detection, and mitigation treatment will yield large net benefits to the Big Island in the form of reduced future costs, damages, and sting incidents.

LFA stings affect people differently. For this reason, we quantified the number of sting incidents without attaching a dollar value and then examined the social tradeoff between cost and human sting incidents through a multi-objective analysis. At the status quo, the marginal cost per sting incident avoided is $0. [45]

Lastly, since the growth and spread rate, as well as the effectiveness of management activities are dependent on random events (e.g. weather, temperature, amount of commerce, etc.) we developed a stochastic specification to examine those uncertainties. The stochastic analysis showed that even under uncertainty, increasing LFA management effort will provide long run economic net benefits.

Explanation of model assumptions

- Units of spread. We estimate LFA spread based on the acreage of impacted sectors. The location and timing where new infestations will occur are unpredictable so we are not able to predict the geographic location of spread. Since our primary goal was to estimate economic impacts, instead we simulated the general tendancy of spread within and between sectors.
- Mechanisms of spread. The probability of spreading between sectors is modeled based on human activity (markets, behaviors, management). These activities determine the rate and manner of LFA spread. Other factors that influence probability, density, and velocity of spread (e.g., weather, temperature, spatial heterogeneity, invasibility) are assumed constant in the deterministic specification, and incorporated jointly in the stochastic specification.
- Locations (farms, business operations, homes, parks, etc.) within sectors are modeled as homogeneous based on average characteristics of the sector.

---

[45] While LFA treatment is not "free", early investment in mitigation efforts will reduce human sting incidents AND reduce future management costs, so the net effect is zero marginal cost.

- Prices. We assumed constant unit prices for chemicals and labor used in treating infestations. The products for LFA are broadly used for treating other ant and insect pests which constitute a much larger market.
- Biodiversity. We did not quantify biodiversity impacts from LFA. More information is needed about the relationship between LFA and native species.
- Interspecies effects. Interspecies competion was excluded based previous work that showed predator, natural enemy, and natural competitor effects are minimal. Interspecies mutualism was excluded based on the assumption that in Hawaii, human habitat and behaviors are the dominant contributors to LFA survival and spread.

Suggestions for future work

- Benefits from new technologies. Our model could be used to evaluate the economic benefit from new technologies. We would require information on the cost and effectiveness of the new technology and any limitations.
- Benefits from improved management practices Our model could be used to evaluate the economic benefit from improved management practices.We would require information on the cost and effectiveness of the improvements compared to exisiting management practices and any limitations.
- Benefit from research in new technologies and management practices. Our model is not designed specifically to evaluate the benefits from research. A new submodel would have to be constructed for that purpose.
- LFA spread to other Hawaiian Islands. Our model could be extended by adding additional “components” and “sectors” to represent the other Hawaiian Islands and relevent economic sectors. We would also require information on the mechanisms of spread and probabilities of occurance.
- Long run effectiveness of biocontrol compared to insecticides. Our model could be used to conduct an economic assessment of biocontrols. We would require information on the cost, effectiveness,and growth characterisitics of the new biocontrols.
- Ecosystem service impacts of LFA. Our model could be used to quantify ecosystem service impacts from LFA. We would require information on how LFA can alter Hawaiian ecosystems.

Acknowledgements

This research was supported in part by the Tropical and Subtropical Agriculture Research (**TSTAR**) Program (Award Number 2010-34135-21228), The National institute of Food and Agriculture (NIFA), US Department of Agriculture (USDA)

We recognize the administrative support provided by our home institution which allowed us to pursue this project.

UH CTAHR

PCSU

We graciously thank all the people who generously responded to our request for help our collaborators and cooperators; the people who took the time to answer questions, respond to our surveys, and provide us with insight and information.

Dave Lau, Owner and Operator, EcoLab pest elimination

Diki Short, Farm manager, College of Agriculture, Forestry and Natural Resource Management, University of Hawaii at Hilo

Jean-Yves MEYER, Délégation à la Recherche

Judy Schilling, Administrator, Hawaii Export Nursery Association

Kim Burnett, UHERO, University of Hawaii at Manoa

Lissa Fox Strohecker, Public Outreach Specialist, Maui Invasive Species Committee (MISC)

Lloyd Loope, US Geologic Survey (USGS), retired

Maryline SIMON, formerly Direction de l'environnement (DIREN)

Page Else, Public Outreach Specialist, Big Island Invasive Species Committee (BIISC)

Pat Conant, Hawaii Department of Agriculture

Robert La Mont, homeowner, Puna Beach Palisades Neighborhood Association

Rogerio Menescal, Property owner and Board member spearheading LFA eradication effort for Puna Beach Palisades Neighborhood Association

Teya Penniman, Maui Invasive Species Committee (MISC)

Tina Yamaki, Executive Director Hawaii Lodging and Tourism Association (HLTA)

Christy Martin, Public Information Officer, Coordinating Group on Alien Pest Species (CGAPS)

Chi Ming (Lawrence) Chan, Accounting officer, CTAHR, UH Manoa

References

Andersen, A. N. (1995). A classification of Austrialian ant communities, based on functional groups which parrallel plant life-forms in relation to stress and disturbance. *Journal of Biogeography, 22*, 15-29

Armbreght, I. (2003). The Little Fire Ant *Wasmannia auropunctata* (Roger) (Hymenoptera: Formicidae) as a diversity indicator of ants in tropical dry forest fragments of Colombia. *Environmental Entomology, 32*, 542-547.

Bossenbroek, J. M., Kraft, C. E., & Nekola, J. C. (2001). Prediction of long-distance dispersal using gravity models: zebra mussel invasion of inland lakes. *Ecological Applications, 11*(6), 1778-1788.

Braness, G. A. (2002). Ant Bait Development: An Imidacloprid Case Study. *Fourth International Conference on Urban Pests.*

Bureau of Labor Statistics (BLS, 2013), Inflation calculator, http://www.bls.gov/data/inflation_calculator.htm

Burnett, K. M., Kaiser, B. A., & Roumasset, J. A. (2007). Economic Lessons from Control Efforts for an Invasive Species: *Miconia calvescens* in Hawaii. *Journal of Forest Economics, 13*, 151-167.

Causton, C. E., Sevilla, C. R., & Porter, S. D. (2005). Eradication Of The Little Fire Ant, *Wasmannia auropunctata* (Hymenoptera: Formicidae), From Marchena Island, Galápagos: On The Edge Of Success? *Florida Entomologist, 88*(2), 159-168.

Conant, P., & Hirayama, C. (2000). *Wasmannia auropunctata* (Hymenoptera:Formicidae): established on the Island of Hawaii. *Bishop Museum Occasional Papers, 64*, 21-22.

Costa, H. S., Greenberg, L., Klotz, J., & Rust, M. K. (2005). Response of Argentine ants and red imported fire ants to permethrin-impregnated plastic strips: Foraging rates, colonization of potted soil, and differential mortality. *Journal of Economic Entomology, 98*(6), 2089-2094.

Fabres, G. and Brown, W. (1978). The recent introduction of the pest ant *Wasmannia auropunctata* into New Caledonia. *Journal of the Australian Entomological Society, 17*, 139-142.

Fasi, J., Brodie, G., and Vanderwoude, C. (2013). Increases in crop pests caused by *Wasmannia auropunctata* in Solomon Islands subsistence gardens. *Journal of Applied Entomology*, *137*, 580-588.

Feder, G. (1979). Pesticides, Information, and Pest Management under Uncertainty. *American Journal of Agricultural Economics, 61*(1), 97-103.

Follett, P. A., & Taniguchi, G. (2007). Effect of irradiation on the longevity and reproduction of Pheidole megacephala (Hymenoptera: Formicidae) queens. *Proceedings of the Hawaiian Entomological Society, 39*, 43-48.

Foucaud, J., Fournier, D., Orivel, J., Delabie, J. H. C., Loiseau, A., Le Breton, J., Kergoat, G. J., and Estoup, A. (2007). Sex and Clonality in the Little Fire Ant. *Molecular Biology and Evolution, 24*, 2465-2473.

Foucaud, J., Orivel, J., Loiseau, A., Delabie, J. H. C., Jourdan, H., Konghouleux, D., Vonshak, M., Tindo, M., Mercier, J. L., Fresneau, D., Mikissa, J. B., McGlynn, T., Mikheyev, A. S., Oettler, J. and Estoup, A. (2010). Worldwide invasion by the little fire ant: routes of introduction and eco-evolutionary pathways. *Evolutionary Applications, 3*, 363–374. doi: 10.1111/j.1752-4571.2010.00119.x

Fournier, D., J. Foucaud, A. J., Loiseau, S. A., Cros-Arteil, H. S., Jourdan, J. H., Orivel, J., Le Breton, J., Chazeau, J., Dejean, A. De Jean, L. ., Keller, L. and Estoup, A. (2005). Characterization and PCR multiplexing of polymorphic microsatellite loci for the invasive ant *Wasmannia auropunctata*. Molecular Ecology Notes, 5, 239-242. doi: 10.1111/j.1471-8286.2005.00889.

Gelatt, N. K. (1999). *Veterinary Ophthalmology*. Lippincott Williams & Wilkins.

Hara et al. (2011). Bait Insecticides and Hot Water Drenches against the Little Fire Ant, *Wasmannia auropunctata* (Hymenoptera: Formicidae), Infesting Containerized Nursery Plants. *Florida Entomologist*, *94*(3), 517-526.

Harris, R., Abbott, K., & Lester, P. (2012). *Invasive Ant Risk Assessment - Wasmannia auropunctata*. Retrieved April 10, 2012, from Manaaki Whenua - Landcare Research: http://www.landcareresearch.co.nz/research/biocons/invertebrates/Ants/invasive_ants/documents/wasaur.pdf

Hastings, A., Cuddington, K., Davies, K. F., Dugaw, C. J., Elmendorf, S., Freestone, A., . . . Thomson, D. (2005). The spatial spread of invasions: new developments in theory and evidence. *Ecology Letters, 8*(1), 1461-0248. Retrieved from http://dx.doi.org/10.1111/j.1461-0248.2004.00687.x

Hawaii State Office of Planning. (2006). *Report on Urban Lands in the State of Hawaii: Part 1: Supply of Urban Lands by Island and Geographic Planning District.* State of Hawaii, Department of Business, Economic Development & Tourism. Honolulu: Hawaii State Office of Planning. Retrieved from http://hawaii.gov/dbedt/op/projects/urban_lands_study/

Hedges, S. A. (1998). *Field Guide for the Management of Structure-Infesting Ants.* (D. Moreland, Ed.) Cleveland, Ohio: Franzak & Foster.

Holldobler, B. and E. O. Wilson. (1990). The Ants. Springer-Verlag, USA.

Holmes, E. E., Lewis, M. A., Banks, J. E., & Veit, R. R. (1994). Partial Differential Equations in Ecology: Spatial Interactions and Population Dynamics. *Ecology, 75*(1), 17-29. Retrieved from http://www.jstor.org/stable/1939378

Holway, D. A., Lach, L., Suarez, A. V., Tsutsui, N. D., & Case, T. J. (2002). The Causes and Consequences of Ant Invasions. *Annual Review of Ecology and Systematics, 33*, 181-234. Retrieved from http://www.jstor.org/stable/3069261

Invasive Species Specialist Group. (2009). *Wasmannia auropunctata* (insect) - Ecology. Retrieved May 15, 2012, from Global Invasive Species Database: http://www.issg.org/database/species/ecology.asp?si=58

Jourdan, H. (1997). Threats on Pacific Islands: The Spread of the Tramp Ant *Wasmannia auropunctata* (Hymenoptera: Formicidae). *Pacific Conservation Biology, 3*(1), 61-64. Retrieved from <http://search.informit.com.au/documentSummary;dn=683644697077378;res=IELHSS>

Klotz, J. H., Rust, M. K., Gonzalez, D., Greenberg, L., Costa, H., Phillips, P., Gispert, C., Reierson, D. A., and Kido, K. (2003). Directed sprays and liquid baits to manage ants in vineyards and citrus groves. *Journal of Agricultural and Urban Entomology*, *20*, 31-40.

Kot, M., & Schaffer, W. M. (1986). Discrete-time growth-dispersal models. *Mathematical Biosciences, 80*(1), 109–136. Retrieved from http://dx.doi.org/10.1016/0025-5564(86)90069-6

Kraus, F. and Duffy, D. C. (2010). A successful model from Hawaii for rapid response to invasive species. *Journal for Nature Conservation, 18*, 135-141.

Krushelnycky, P.D., Haines, W., Loope, L., and Van Gelder, E. (2011). The Haleakala Argentine ant project: a synthesis of past research and prospects for the future. Pacific Cooperative Studies Unit Technical Report 173. University of Hawai‘i at Mānoa, Department of Botany.

Krushelnycky, P. D., Loope, L. L., & Reimer, N. J. (2005). The Ecology, Policy, and Management of Ants in Hawaii. *Proceedings of the Hawaiian Entomological Society, 37*, 1–25. Retrieved from http://hdl.handle.net/10125/103

La Croix, S. (2010). *Economic History of Hawai'i*. Retrieved November 12, 2011, from Economic History Association: http://eh.net/encyclopedia/article/lacroix.hawaii.history

Leung, B., Lodge, D. M., Finnoff, D., Shogren, J. F., Lewis, M. A., & Lamberti, G. (2002). An Ounce of Prevention or a Pound of Cure: Bioeconomic Risk Analysis of Invasive Species. *Biological Sciences, 269*(1508), 2407-2413. Retrieved from http://www.jstor.org/stable/3558671

Levy, R., Y. J. Chiu, Y. J., and Banks, W. A. Banks. (1973). Laboratory evaluation of candidate bait toxicants against the Red Imported Fire Ant *Solenopsis invicta*. *Florida Entomologist, 56*, 141-146.

Loope, L. L. (1998). Hawaii and Pacific islands. (Mac, M. J., Opler, P. A., Puckett Haecker, C. E., & Doran, P. D., Eds.) *Status and Trends of the Nation's Biological Resources*, 747-774. Retrieved from http://www.hear.org/articles/pdfs/hawaii_and_the_pacific.pdf

Loope, L. L., & Mueller-Dombois, D. (1989). Characteristics of invaded islands, with special reference to Hawaii. *Biological invasions a global perspective*, 257-280. Retrieved from http://www.scopenvironment.org/downloadpubs/scope37/scope37.html

Lowe, S., Browne, M., Boudjelas, S. M., and De Poorter, M. (2000). 100 of the World's Worst Invasive Alien Species: A Selection from the Global Invasive Species Database. World Conservation Union (IUCN), Auckland, New Zealand.

Lubin, Y. D. (1984). Changes in the native fauna of the Galapagos Islands following invasion by the Little Red Fire Ant, *Wasmannia auropunctata*. *Biological Journal of the Linnean Society*, *21*, 229-242.

Mack, R. N., D. Simberloff, W. M.D., Lonsdale, H.W. M., Evans, M.H., Clout, M., and Bazzazm F. A. (2000). Biotic invasions: causes, epidemiology, global consequences and control. *Ecological Applications, 10*, 689-710.

Marco, D. E., Páez, S. A., & Cannas, S. A. (2002). Species Invasiveness in Biological Invasions: A Modelling Approach. *Biological Invasions, 4*(1), 193-205.

McGlynn, T. P. (1999). The worldwide transfer of ants: geographical distribution and ecological invasions. *Journal of Biogeography*, *26*.

Mehta, S. V., Haight, R. G., Homans, F. R., Polasky, S., & Venette, R. C. (2007). Optimal detection and control strategies for invasive species management. *Ecological Economics, 61*(2-3), 237-245. Retrieved from http://www.sciencedirect.com/science/article/pii/S0921800906005568

Nathan, R., Perry, G., Cronin, J. T., Strand, A. E., & Cain, M. L. (2003). Methods for estimating long-distance dispersal. *Oikos, 103*(2), 261–273. doi:10.1034/j.1600-0706.2003.12146.x

Olson, L. (2006). The Economics of Terrestrial Invasive Species: A Review of the Literature. *Agricultural and Resource Economics Review, 35*(1), 178-194. Retrieved from http://ageconsearch.umn.edu/bitstream/10181/1/35010178.pdf,%20A%20Lit%20Review.pdf

Olson, L., & Roy, S. (2003). The Economics of Controlling a Biological Invasion. *Working Paper No. 03-06*.

Lowe S., Browne M., Boudjelas S., De Poorter M. (2000) 100 of the World's Worst Invasive Alien Species A selection from the Global Invasive Species Database. Published by The Invasive Species Specialist Group (ISSG) a specialist group of the Species Survival Commission (SSC) of the World Conservation Union (IUCN), 12pp. First published as special lift-out in Aliens 12, December 2000. Updated and reprinted version: November 2004. http://www.issg.org/database/species/reference_files/100English.pdf

Samways, M. J. (1990). Species temporal variability: epigaeic ant assemblages and management for abundance and scarcity. *Oecologia, 84*(4), 482-490.

Scanlan, J. C. and Vanderwoude, C. (2006). Modelling the potential spread of Solenopsis invicta Buren (Hymenoptera: Formicidae) (red imported fire ant) in Australia. *Australian Journal of Entomology, 45*, 1-9.

Scanlan, J. C., Vanderwoude, C. (2009), Modelling the potential spread of *Solenopsis invicta* Buren (Hymenoptera: Formicidae) (red imported fire ant) in Australia, 33pp, manuscript.

Smith, M. R. (1929). Two introduced ants not previously known to occur in the United States. *Journal of Economic Entomology, 22*, 241-243.

Souza, E., Follett, P. A., Price, D. K., & Stacy, E. A. (2008). Field Suppression of the Invasive Ant Wasmannia auropunctata (Hymenoptera: Formicidae) in a Tropical Fruit Orchard in Hawaii. *Journal of Economic Entomology*, 1068-1074.

Starr, F., Starr, K., & Loope, L. L. (2008). Survey for ants on the island of Maui, Hawaii, with emphasis on the little fire ant (*Wasmannia auropunctata*), Pacific Cooperative Studies Unit Technical Report 156. University of Hawaiʻi at Mānoa, Department of Botany.

Suarez, A. V., Holway, D. A., & Case, T. J. (2001). Patterns of Spread in Biological Invasions Dominated by Long-Distance Jump Dispersal: Insights from Argentine Ants. *Proceedings of the National Academy of Sciences of the United States of America, 98*(3), 1095-1100. Retrieved from http://www.jstor.org/stable/3054827

Theron, L. (2005). Hypothèse d'une kératopathie liée à *Wasmannia auropunctata*, le modèle polynésien. masters. University de Liege.

Tollerup, K. E., M. K. Rust, M. K. W.., Dorschner, P. A.K. W., Phillips, P. A., and Klotz, J. H. Klotz. (2004). Low-toxicity baits control ants in citrus orchards and grape vineyards. *California Agriculture, 58*, 213-217.

Vanderwoude, C., Onuma, K., & Reimer, N. (2010). Eradicating *Wasmannia Auropunctata* (Hymenoptera: Formicidae) from Maui, Hawaii: The use of combination treatments to control an arboreal invasive ant. *Proceedings of the Hawaiian Entomological Society, 42*, 23-31.

Vonshak, M., T. Dayan, A.T. Ionescu-Hirsh, A. Freidberg and A. Hefetz (2010). The little fire ant *Wasmannia auropunctata*: a new invasive species in the Middle East and its impact on the local arthropod fauna.*Biological Invasions, 12*, 1825- 1837.

Wetterer, J. K., & Porter, S. D. (2003). The Little Fire Ant, *Wasmannia Auropunctata*: Distribution, Impact and Control. *Sociobiology, 42*(3), 1-41.

Williams, D. (1983). The development of toxic baits for the control of the Imported Fire Ant. *Florida Entomologist*, *66*, 162-172.

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

Wilson, J. R., Dormontt, E. E., Prentis, P. J., Lowe, A. J., & Richardson, D. M. (2009). Something in the way you move: dispersal pathways affect invasion success. *Trends in Ecology & Evolution, 24*(3), 136-144. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169534709000202

Appendix A – Deterministic analysis

Management of LFA on the Big Island currently includes identification, information outreach and assistance, and technology development. Ongoing education and public engagement is provided by the Big Island Invasive Species Committee (BIISC) in conjunction with other island invasive species committees (ISCs). In addition, Hawaii Department of Agriculture (HDOA) enforces Hawaii's invasive species laws which regulate all imported plants and animals.

Economic implications of status quo management

Under status quo management, in the coming 5 years, LFA will spread on the Big Island infesting 31%, 50, 60% and 52% of the nursery, lodging, park, and school sectors. In the agriculture and residential sectors LFA will continue to spread peaking at 35% and 38% in 15 to 20 years.

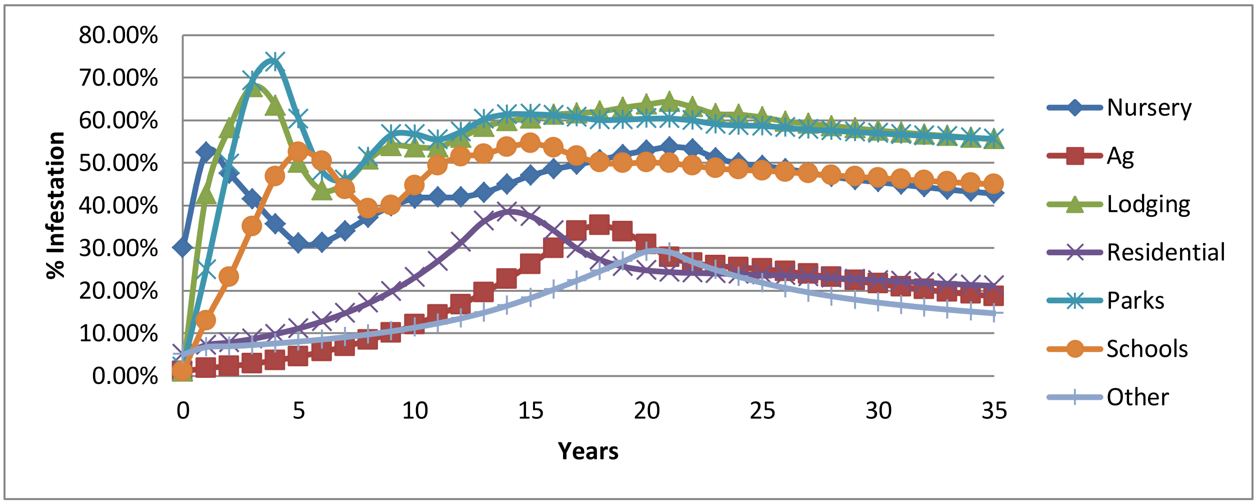


Figure 34 LFA infestation with status quo management

Agriculture, schools and parks incur the highest costs. Residences, parks, schools, and lodging establishment incur the greatest number of sting incidents. Across all sectors, the present value total cost is $6.1 billion and total sting incidents are 2.3 billion.

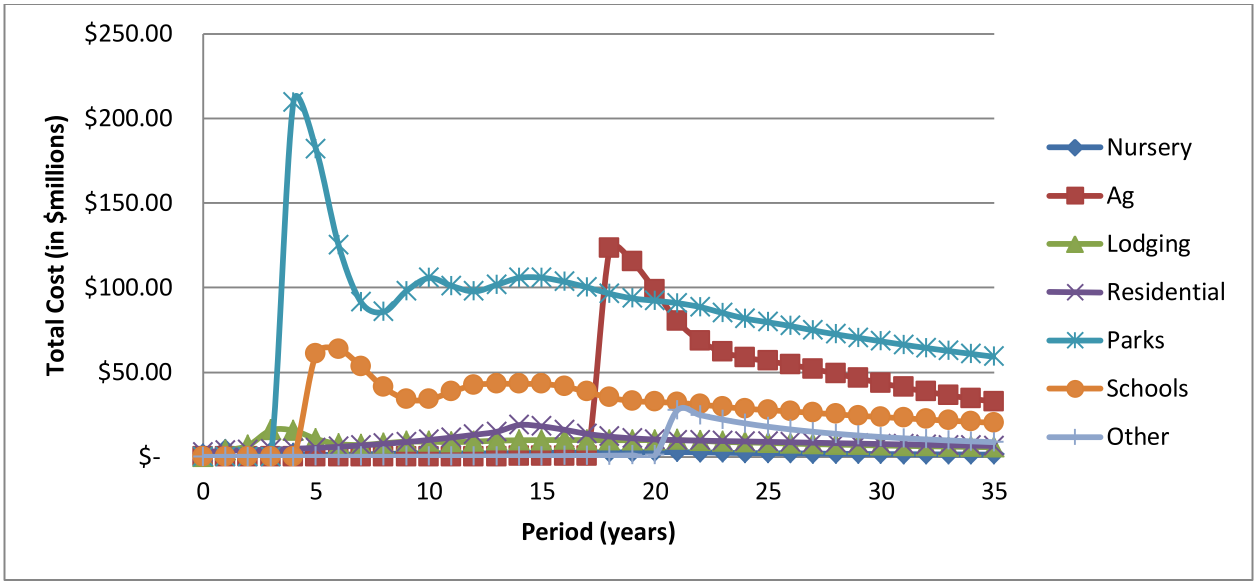


Figure 35 Cost of LFA infestation with status quo management

Table 20 Total cost and total human stings over 35 years with status quo management

Sector	Damage Cost (as % of total)	Mitigation Treatment Cost (as % of total)	PV of Total Cost (in $millions)	LFA Human Stings (in millions of incidences)
Nursery	93%	7%	76.06	16.08
Agriculture	0%	100%	1091.44	7.04
Lodging	57%	43%	301.38	372.12
Residential	90%	10%	324.75	766.77
Parks	0%	100%	2996.97	485.77
Schools	0%	100%	1058.29	457.02
Other	5%	95%	236.30	150.17
Total	**9%**	**91%**	**6085.20**	**2254.97**

Economic implications of least cost management

Under least cost management, the number of LFA infested sites decrease overtime in the nursery and lodging and school sectors, but are not immediately suppressed. Suppression across all sectors is achieved within 15 years. Infested areas are treated immediately to slow new growth and reduce spread. Prevention and detection measures are used to reduce the rate at which LFA establishes in new locations.

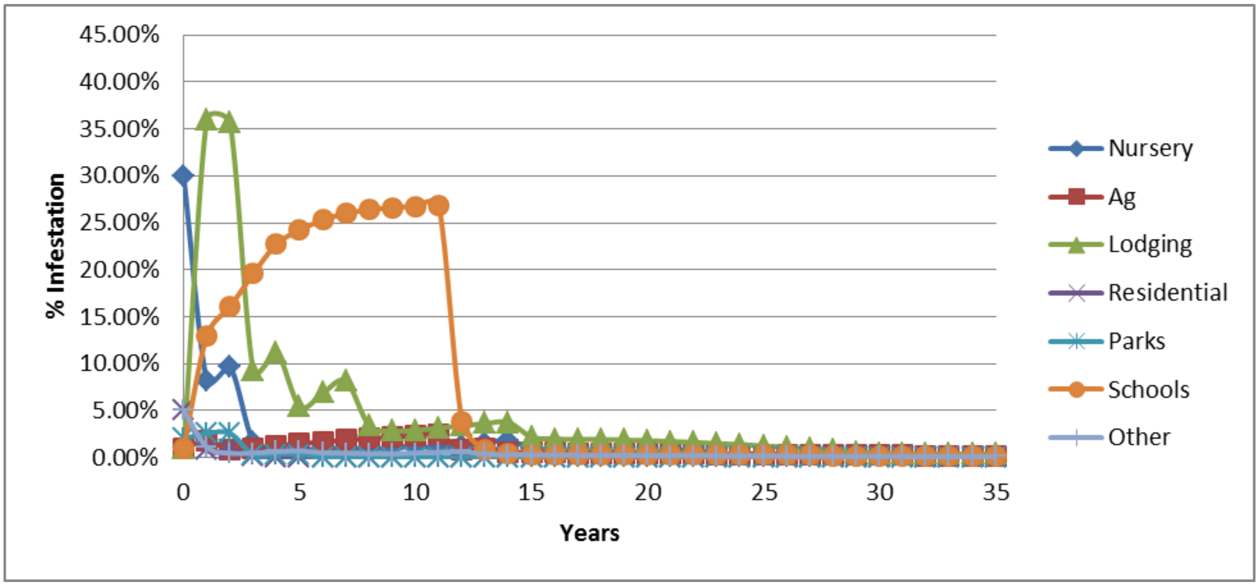


Figure 36 LFA infestation by sector with least cost management

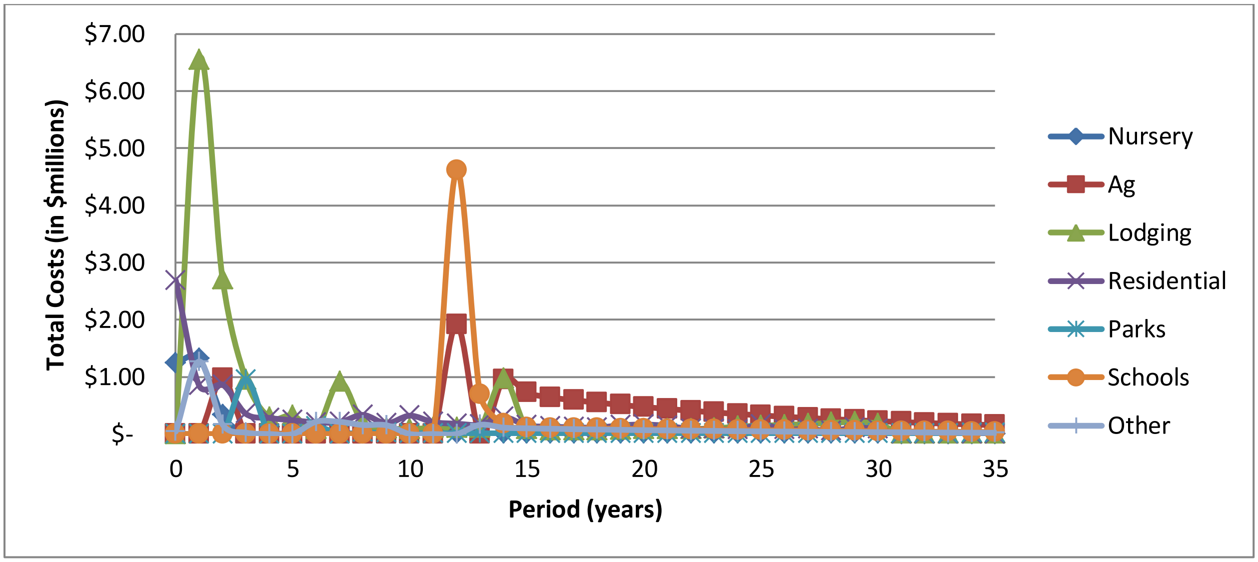


Figure 37 Annual cost of LFA infestation by sector with least cost management

With least cost management, mitigation, prevention, and detection expenditures total $39.8 million; damages total $11.2 million.

Given the current 128,899 infested acres, average management expenditure is $309 an acre, significantly lower than the monies spent eradicating LFA in the Galapagos, $4890[46] per acre (Causton, Sevilla, & Porter, 2005).

Table 21 Cost distribution and stings over 35 years under least cost management

Sector	**Cost distribution (% of total)**				**PV Total Cost $million**	**LFA Human Stings[a]**	
	Damage	Mitigation Treatment	Detection	Prevention		Reduction million	Reduction %
Nursery	47.3%	2.8%	13.8%	36.4%	3.13	15.69	97.6%
Ag	0.1%	121.2%	0.0%	0.0%	11.46	6.85	97.4%
Lodging	38.8%	17.8%	34.1%	10.3%	15.47	369.61	99.3%
Residential	39.2%	2.5%	0.0%	58.3%	9.20	763.67	99.6%
Parks	0.0%	185.8%	0.0%	0.0%	1.47	484.60	99.8%
Schools	0.0%	108.3%	0.0%	0.0%	6.92	424.41	92.9%
Other	1.4%	108.3%	0.0%	0.0%	3.62	149.69	99.7%
Total	**21.8%**	**60.7%**	**11.1%**	**15.8%**	**51.26**	**2214.53**	**98.2%**

[a] Reductions are relative to the Status Quo levels of sting incidents.

Prevention expenditures are largest in the nursery and residential sectors, where initial infestations are most widespread. Mitigation treatment is highest in the park, agriculture, and school sectors which are geographically large.

The number of LFA sting incidents corresponds to LFA infestation levels. Stings incidents are high during the first few years then decline with infestation levels. LFA sting incidents are highest initially in the school sector and then taper as infestation declines. Compared to the Status Quo scenario, the Least Cost management reduces sting incidents by 2.2 billion over 35-years, 63 million fewer stings per year or 226 fewer stings per person per year.

---

[46] The 2005 Causton, Sevilla & Porter figure of $4100 has been adjusted for inflation.

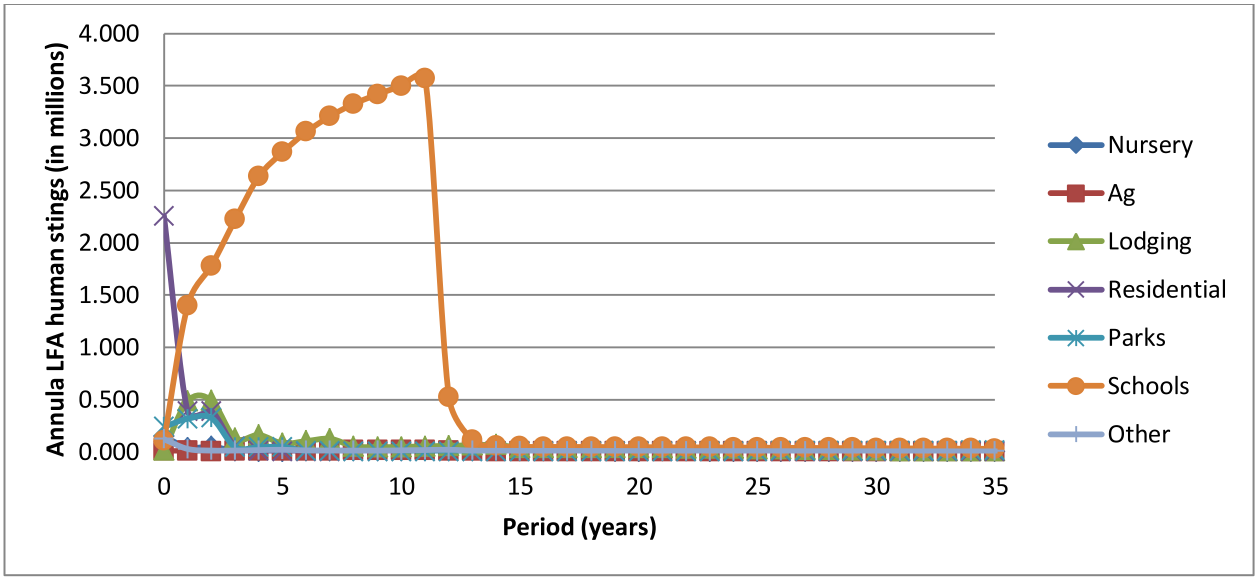


Figure 38 Annual LFA sting incidents by sector with least cost management

Economic implications of eradication management

In the eradicate LFA model, we look at the outcome of the LFA invasion if all sectors undertake sufficient management efforts to "eradicate" LFA on the Big Island. Here we consider overall sector infestation levels of less than 1% to be "eradicated." We assume that all sectors undertake mitigation, prevention, and detection efforts if the overall infestation level is larger than 2.5%. We assume that if mitigation treatment is taken, then the maximum amount of mitigation effort is employed (i.e., $d_i^{mitgate} = 4$ regardless of the overall infestation level). However, the management effort for prevention and detection is proportional to the overall level of infestation N_i^{final} and the maximum allowable management effort.

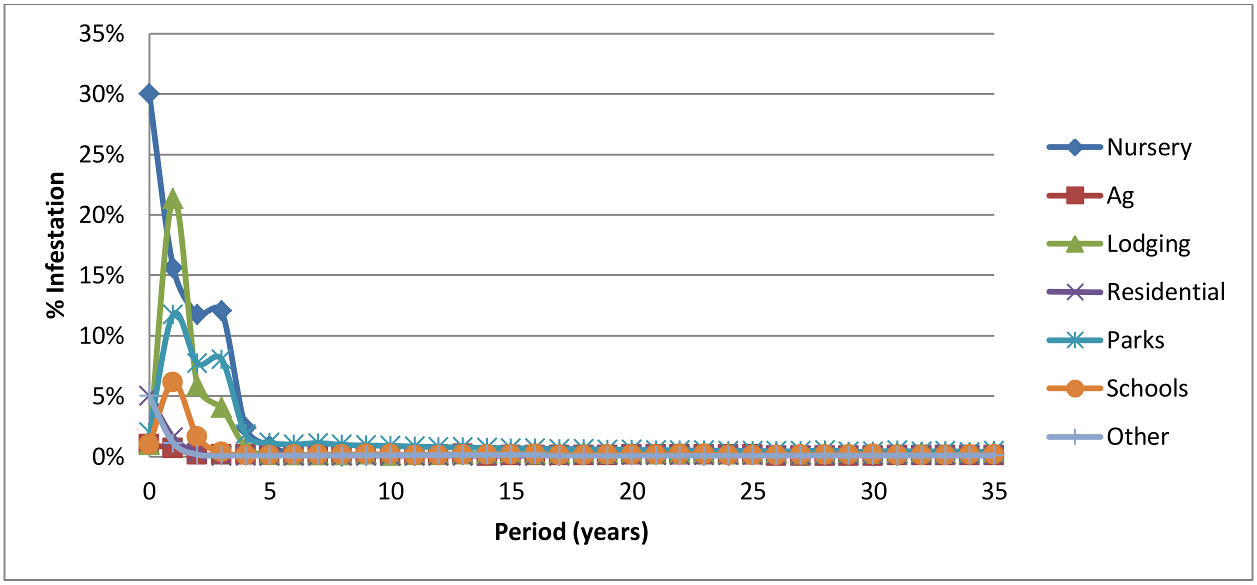


Figure 39 LFA infestation by sector with eradication management

Infestation levels are suppressed in all sectors to below 5% in the first two years, and are further reduced to less than 1% by year eight. In followingyears, a very low level of infestation is maintained for duration of the model.

Eradication management expenditures for prevention, detection, and mitigation are $555 million generated over 35 years. Damages are $6.72 million. Total costs are $561 million. LFA sting incidents are reduced by about 64 million per year on average or 227 fewer stings per person per year.

Given the current infested area of 128,899 acres, management expenditure is $1,588 per acre in the first year and $4,357 per acre over 35 years on average. The 35 year average cost of management is quiet similar to the expenditures for eradicating LFA in the Galapagos, $4890 per acre (Causton, Sevilla, & Porter, 2005).

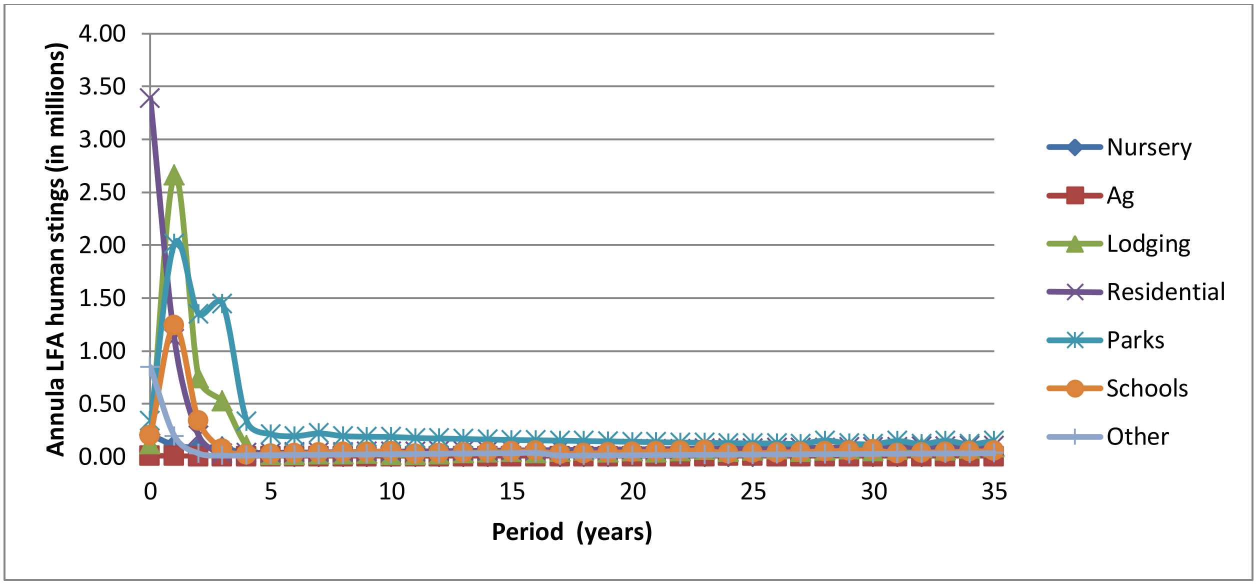


Figure 40 LFA stings by sector with eradication management

Table 22 Cost distribution and stings over 35 years with eradication management

Sector	Cost distribution (as a % of total)				PV Total Cost $millions	LFA Human Stings[a]	
	Damage	Mitigation Treatment	Detection	Prevention		Reduction million	Reduction %
Nursery	59%	12%	10.3%	19.0%	1.68	15.53	96.6%
Ag	0%	41%	59%	0%	12.42	6.99	99.3%
Lodging	5%	18%	28%	49%	22.60	366.50	98.5%
Residential	86%	5%	9%	0%	5.39	759.88	99.1%
Parks	0%	29%	33%	38%	350.18	475.55	97.9%
Schools	0%	8%	14%	78%	163.95	453.91	99.3%
Other	1%	39%	61%	0%	5.41	148.39	98.8%
Total	**1%**	**23%**	**28%**	**48%**	**561.63**	**2226.75**	**98.7%**

[a] Reductions are relative to the Status Quo levels of sting incidents.

Economic implications of least sting management

Least sting management requires early mitigation, prevention, and detection efforts to prevent the dispersal of existing LFA. Infestation levels are suppressed in all sectors to below 5% in the first two years.

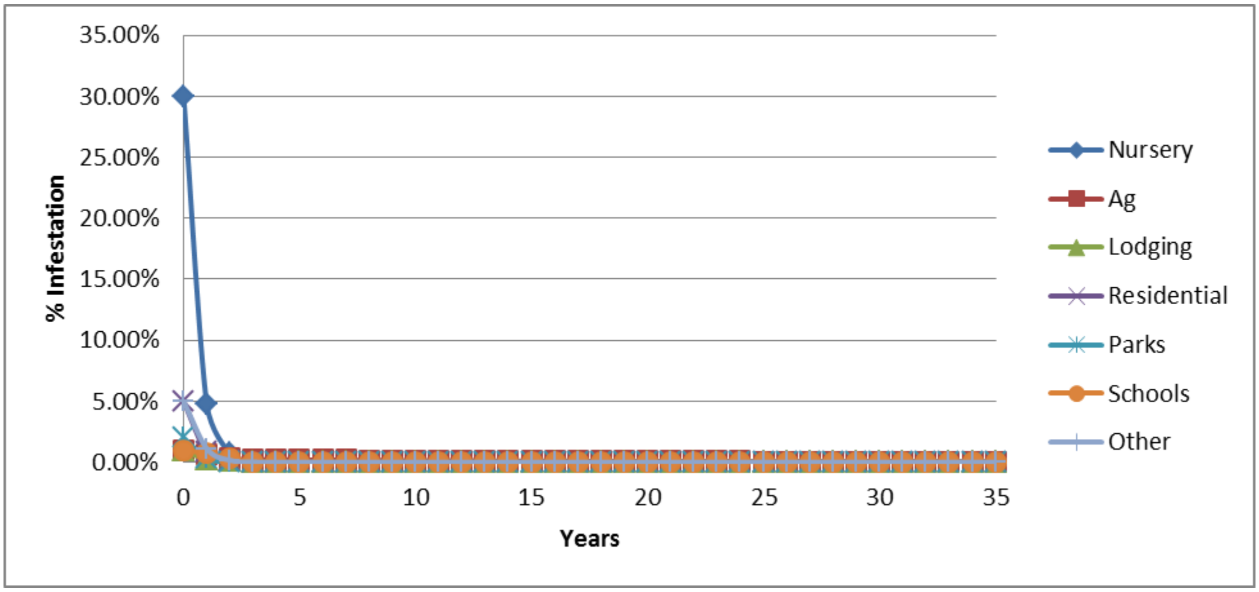


Figure 41 LFA infestation by sector with least sting management

Least sting management expenditures for prevention, detection, and mitigation are $939 million generated over 35 years. Damages are $4.52 million. Total costs are $950 million. LFA sting incidents are reduced by 64 million per year or 230 fewer stings per person per year.

Given the current infested area of 128,899 acres, average management expenditure is $5565 per acre in the first year and $7,288 per acre over 35 years, comparable to the expenditures for eradicating LFA in the Galapagos, $4890 per acre (Causton, Sevilla, & Porter, 2005).

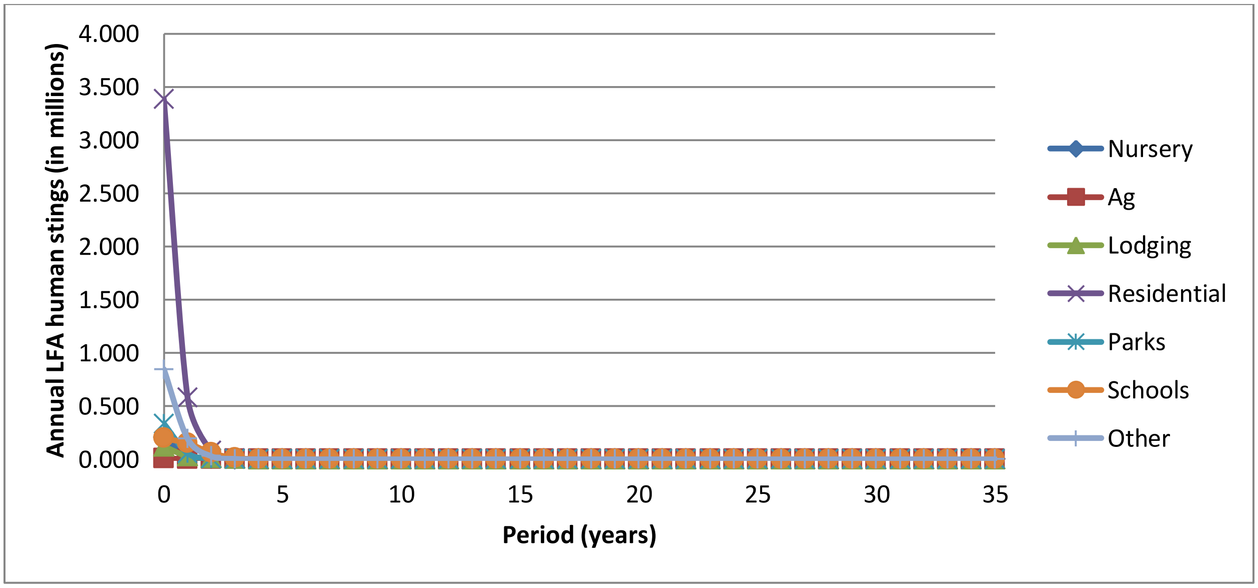


Figure 42 LFA stings by sector with least sting management

Table 23 Cost distribution and stings over 35 years with least sting management

Sector	**Cost distribution (as a % of total)**				**PV Total Cost $millions**	**LFA Human Stings[a]**	
	Damage	Mitigation Treatment	Detection	Prevention		Reduction million	Reduction %
Nursery	16.8%	0.5%	11.3%	71.4%	7.59	15.91	98.9%
Ag	0.0%	7.9%	92.6%	0.0%	106.52	7.00	99.5%
Lodging	0.0%	0.0%	13.3%	86.9%	123.40	372.10	100.0%
Residential	36.4%	1.4%	0.0%	112.7%	8.79	764.07	99.6%
Parks	0.0%	0.2%	0.0%	99.8%	474.64	485.48	99.9%
Schools	0.0%	1.2%	98.8%	0.0%	129.17	456.78	99.9%
Other	0.0%	2.1%	97.9%	0.0%	94.07	150.01	99.9%
Total	**0.5%**	**1.4%**	**35.5%**	**63.1%**	**944.18**	**2251.36**	**99.8%**

[a] Reductions are relative to the Status Quo levels of sting incidents.

Economic implications of reduced management

Under reduced management in the coming 5 years, LFA will spread on the Big Island 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. 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 LFA is $12.9 billion. The total number of LFA sting incidents to children, adults and visitors over 35 years is 3.4 billion.

Under reduced LFA management, LFA will spread rapidly on the Big Island infesting 54%, 66%, 71, and 54% of the nursery, lodging, park, and school sectors over the next five years. LFA spread in the agriculture and residential sectors, peaking at 47% and 51% within 25 years.

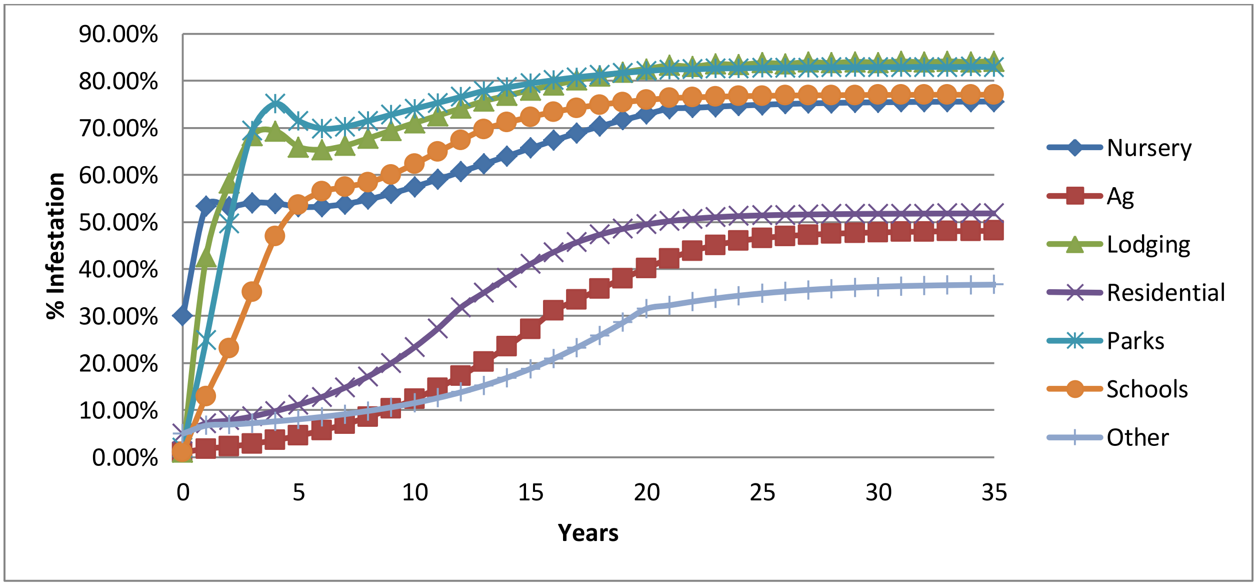


Figure 43 LFA infestation by sector under reduced LFA management

Although most sectors save on reduced management expenditures, the amount of damages and the number of stings greatly increases. Compared to the status quo management scenario, the overall number of LFA sting incidents increases by 50%. The total amount of monetary damages increase by 62%, and all sector have higher long run infestation levels.

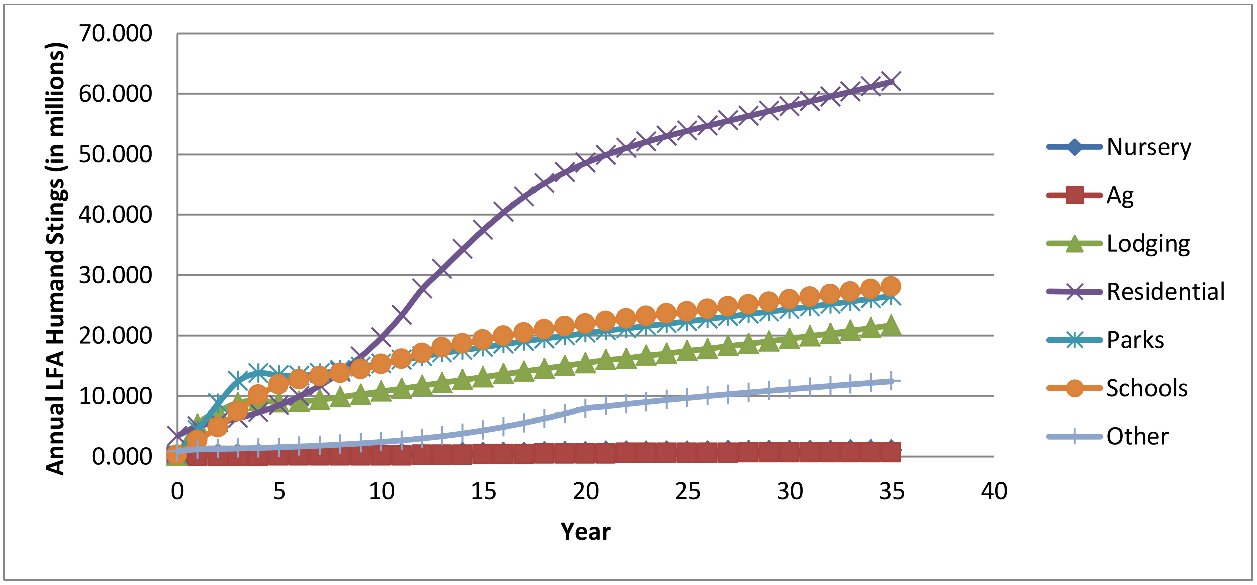


Figure 44 Annual LFA stings by sector under reduced LFA management

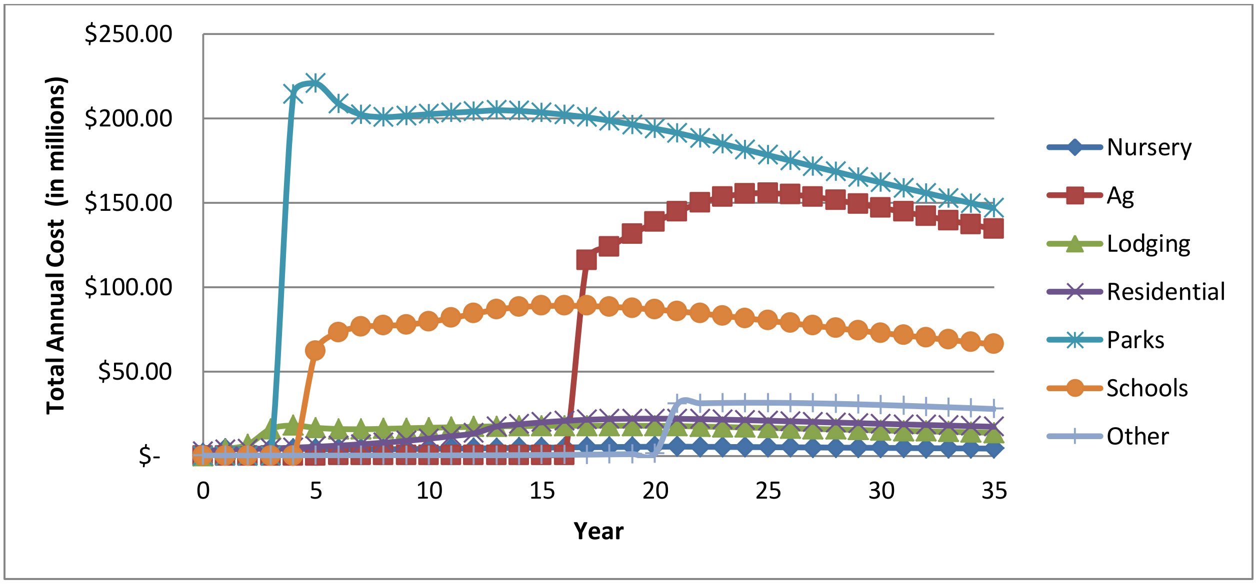


Figure 45 Total annual cost by sector under reduced LFA management

Table 24 Cost distribution and stings over 35 years under reduced LFA management

Sector	Cost Distribution		PV Total Cost	LFA Human Stings	
	Damage	Mitigation Treatment	$ million	Million incidences	Percent increase over SQ
Nursery	92%	8%	162	24	50.5%
Agriculture	0%	100%	2722	12	65.2%
Lodging	54%	46%	550	503	35.3%
Residential	84%	16%	547	1329	73.3%
Parks	0%	100%	5990	661	36.0%
Schools	0%	100%	2450	677	48.1%
Other	6%	94%	460	223	48.9%
Total	**7%**	**93%**	**12880**	**3429**	**52.0%**

Appendix B - Sensitivity analysis

Table 25 Sensitivity results under status quo management

No.	**Sensitivity test**				**Year 10**		**Steady state**			**Total Cost (after 35 years**
	Parameter	Units	Base Value	Test value	% infested	Annual sting incidents (in millions)	Year	% infested	Annual sting incidents (in millions)	
1	Base	N/A	N/A	N/A	18.7%	53	20	27.2%	74	$6,085
1-i	Growth and spread	years	13	7	33.3%	79	15	35.1%	83	$8,209
1-ii				20	6.4%	18	10	6.4%	18	$1,584
2-i	Management cost	$ per acre per day	$15	$7.50	18.7%	53	20	27.2%	74	$6,085
2-ii				$30	18.7%	53	20	27.2%	74	$6,085
3-i	Damage, sting incidents	$ per incident	$0	$5.00	18.7%	53	20	27.2%	74	$13,758
3-ii				$25	18.7%	53	20	27.2%	74	$44,448
4-i	Damage, ecosystem	$ per acre in PARKS	$0	$25.00	18.7%	53	20	27.2%	74	$6,086
4-ii				$250	18.7%	53	20	27.2%	74	$6,095
5-i	Establishment rate	%	10%	5%	18.7%	53	20	27.2%	74	$6,085
5-ii				1%	18.7%	53	20	27.2%	74	$6,085
6-i	Discount rate	%	2%	4%	18.7%	53	20	27.2%	74	$4,282
6-ii				8%	18.7%	53	20	27.2%	74	$2,354
7-i	Mitigation effectiveness	% per application	40%	60%	18.6%	52	21	25.0%	69	$5,196
7-ii				80%	18.5%	51	21	23.6%	66	$4,904
8-i	Detection success	%	25%	50%	18.7%	53	20	27.2%	74	$6,085
8-ii				99%	18.7%	53	20	27.2%	74	$6,085

Table 26 Sensitivity results under least cost management results

No.	**Sensitivity test**				**Year 10**		**Steady state**			**Total Cost (after 35 years**
	Parameter	Units	Base Value	Test value	% infested	Annual sting incidents (million)	Year	% infested	Annual sting incidents (million)	
1	Base	N/A	N/A	N/A	0.05%	1.66	9	0.05%	1.64	$30.46
1-i	Growth and spread	years	13	7	4.82%	7.10	20	0.47%	0.49	$51.26
1-ii				20	0.04%	1.51	4	0.23%	1.55	$25.26
2-i	Management cost	$ per acre per day	$15	$7.50	0.05%	1.66	9	0.05%	1.64	$26.41
2-ii				$30	0.05%	1.66	9	0.05%	1.64	$38.54
3-i	Damage, sting incidents	$ per incident	$0	$5.00	0.05%	1.40	5	0.09%	1.33	$187.61
3-ii				$25	0.00%	0.00	5	0.03%	0.02	$311.83
4-i	Damage, ecosystem	$ per acre in PARKS	$0	$25.00	0.05%	1.66	9	0.05%	1.64	$30.46
4-ii				$250	0.05%	1.66	9	0.05%	1.64	$30.52
5-i	Establishment rate	%	10%	5%	0.05%	1.66	9	0.05%	1.64	$30.46
5-ii				1%	0.05%	1.66	9	0.05%	1.64	$30.46
6-i	Discount rate	%	2%	4%	0.05%	1.66	9	0.05%	1.64	$27.42
6-ii				8%	0.05%	1.66	9	0.05%	1.64	$23.38
7-i	Mitigation effectiveness	% per application	40%	60%	0.04%	1.67	5	0.15%	1.52	$23.30
7-ii				80%	0.04%	1.66	5	0.15%	1.51	$21.85
8-i	Detection success	%	25%	50%	0.05%	1.66	9	0.05%	1.63	$30.09
8-ii				99%	0.04%	1.53	7	0.05%	1.46	$31.16

Of the eight parameters included in the analysis, the least-cost scenario was most sensitivity to changes in the monetary value of sting incidents (i.e., tests 3-i, and 3-ii). As the damage cost of stings increases, the least cost policy responds by increasing management effort. The additional damages and higher management leads to higher total costs. Higher management, however, allows the steady-state condition to be achieved earlier. Similarly, in these tests, the percent infested at the 10-year mark is reduced.

The growth and spread rate parameter also influenced the least-cost policy. As the growth rate decreases, management efforts are more capable of containing the growth and spread of LFA. Consequently, the steady state is achieved sooner, the total cost decreases, and the steady state number of sting incidents is reduced. Incidentally, this parameter is also one of the most difficult to measure precisely. Therefore, if the actual growth and spread is higher than expected, then damages are likely to be higher and management is likely to be more difficult.

Management effectiveness parameters (i.e., mitigation treatment effectiveness (tests 7-i, 7-2), and detection success rate (tests 8-i, 8-ii)) also influence the least-cost policy. As these parameters increase, the steady state is achieved sooner, and the total cost decreases. In the detection success case, the steady state number of sting incidents is also reduced, while increasing mitigation treatment effectiveness has little effect on the number LFA sting incidents.

Sensitivity analysis of least sting management results

Table 27 shows the results of the sensitivity analysis for the least cost scenario. Since the objective of minimizing stings is not concerned with cost and since there are no optimization constraints other than the maximum levels of management, the least sting scenario maintains its normal policy for all of the sensitivity tests. However, some of the parameters do have a noticeable effect on the least sting scenario results (even though the policy does not change).

The two parameter to significantly affect the least sting policy were 1) the growth and spread rate, 2) the mitigation effectiveness, and 3) detection success. Like the least cost scenario, a decrease in growth and spread rate will improve the relative effectiveness of management and subsequently lower costs, but an increase would likely lead to higher management expenditures and subsequently higher costs and more stings. Direct improvements to management efforts (i.e., tests 7-i, 7ii, 8-i, and 8ii) will also lower costs, and lead to the steady state condition being reached sooner.

Table 27 Sensitivity results under least sting management

No.	**Sensitivity test**				**Year 10**		**Steady state**			**Total Cost (after 35 years)**
	Parameter	Units	Base Value	Test value	% infested	Annual sting incidents (million)	Year	% infested	Annual sting incidents (million)	
1	Base	N/A	N/A	N/A	0.00%	0.00	3	0.02%	0.59	$940.60
1-i	Growth and spread	years	13	7	0.02%	0.072	13	0.02%	0.065	$944.18
1-ii				20	0.00%	0.00	3	0.02%	0.54	$940.38
2-i	Management cost	$ per acre per day	$15	$7.50	0.00%	0.00	3	0.02%	0.59	$644.78
2-ii				$30	0.00%	0.00	3	0.02%	0.59	$1,532.24
3-i	Damage, sting incidents	$ per incident	$0	$5.00	0.00%	0.00	3	0.02%	0.59	$957.86
3-ii				$25	0.00%	0.00	3	0.02%	0.59	$1,026.90
4-i	Damage, ecosystem	$ per acre in PARKS	$0	$25.00	0.00%	0.00	3	0.02%	0.59	$940.60
4-ii				$250	0.00%	0.00	3	0.02%	0.59	$940.64
5-i	Establishment rate	%	10%	5%	0.00%	0.00	3	0.02%	0.59	$940.60
5-ii				1%	0.00%	0.00	3	0.02%	0.59	$940.60
6-i	Discount rate	%	2%	4%	0.00%	0.00	3	0.02%	0.59	$914.90
6-ii				8%	0.00%	0.00	3	0.02%	0.59	$869.01
7-i	Mitigation effectiveness	% per application	40%	60%	0.00%	0.00	2	0.02%	0.53	$937.42
7-ii				80%	0.00%	0.00	2	0.01%	0.32	$936.81
8-i	Detection success	%	25%	50%	0.00%	0.00	3	0.01%	0.50	$940.11
8-ii				99%	0.00%	0.00	3	0.01%	0.49	$940.04

Appendix C – Stochastic analysis

Our stochastic results seemed to be fairly robust, however the deterministic values sometimes seemed to deviate from the stochastic results. This section will give several possible explanations for these discrepancies.

Status quo management

In the stochastic status quo management model, the deterministic percent infestation was consistently lower than the mean value, and roughly approximated the lower bound of the 90% CI. This is probably because the growth and spread mechanisms in the biological submodel have a multiplier effect. In other words, an increase in the starting number of infestations $N_{i,t}^{starting}$ will have a larger absolute change in the final number of infestations $N_{i,t}^{final}$ than compared to an equal decrease in the starting number of infestations. This is especially true for sectors with small starting infestation levels (e.g., the agriculture, lodging, school, and park sectors in the first period), since the growth rate is higher for smaller populations. Increases (and decreases) in infestation levels could come directly from the inclusion of a random variable or indirectly from spread; the high effectiveness curve shows that if management effectiveness is much higher than expected, then the status quo scenario will see a noticeable decrease in overall percent infestation compared to the deterministic case. However, even if management effectiveness is higher than expected, the status quo scenario will still see an increase in overall percent infestation levels compared to starting percentages. The low effectiveness curve shows that if management effectiveness is lower than expected, the overall percent infestation will increase. The low effectiveness curve is about 20% higher than the deterministic percent infestation curve, while the high effectiveness curve is about 31% lower than the deterministic percent infestation curve.

The high effectiveness curve is the only percent infestation curve that doesn't follow the deterministic results. If the management effectiveness is higher than expected, the total cost curve shifts noticeably lower. In some years, the cumulative total cost for high effectiveness case is as much as 70% lower than the deterministic value. By the end of year 35, the cumulative total cost for high effectiveness case is 45% lower than the deterministic value (or \$2.8 billion less than the deterministic total cost). However, a decrease in management effectiveness does not have a large influence on the total cost. For the low effectiveness case, the cumulative total cost is 10% higher than the deterministic value by the end of year 35 (or about \$650 million higher than the deterministic total cost). A possible explanation could be that the saving from improved management effectiveness compounds over time. Improved management reduces the cost of combating an infestation, and reduces the size of infestation, which means that less money will need to be spent in the future.

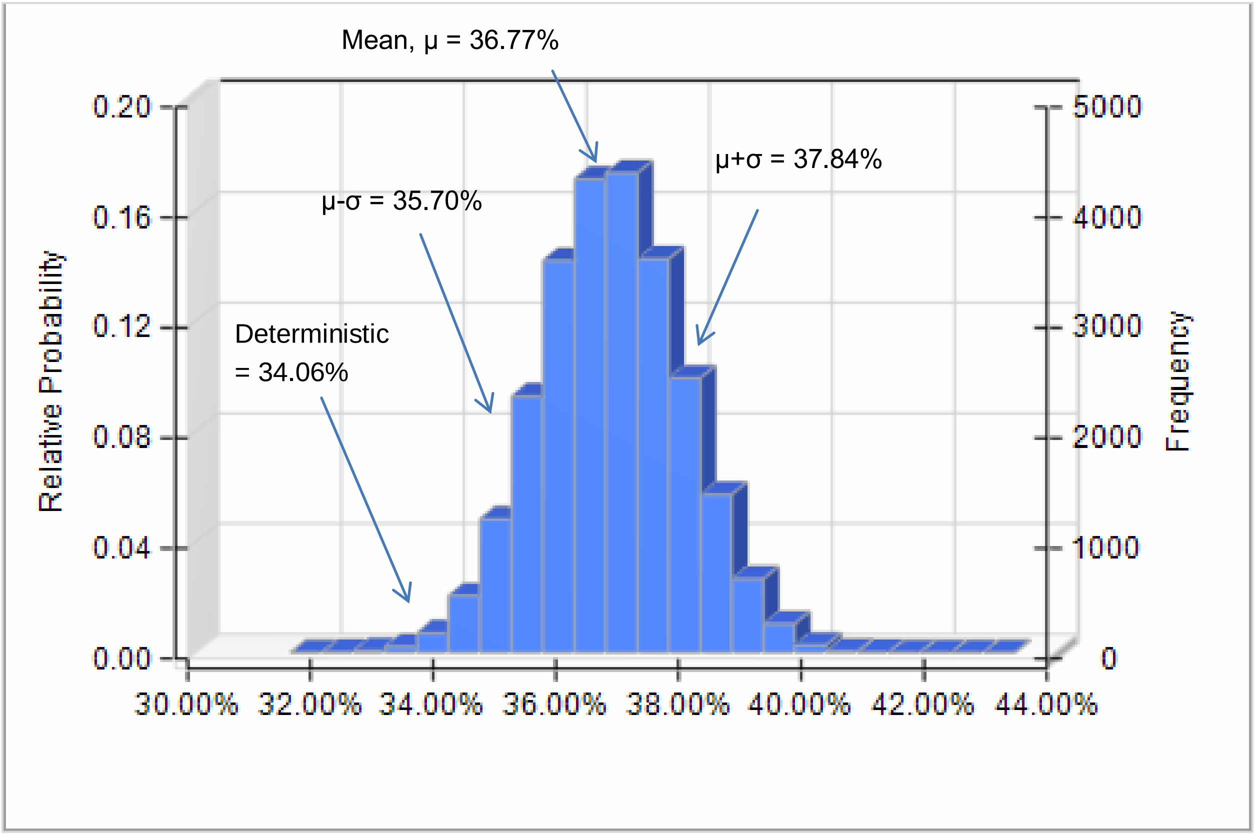


Figure 46 Status quo management – Impact of management on probable % LFA infestation in year 35.

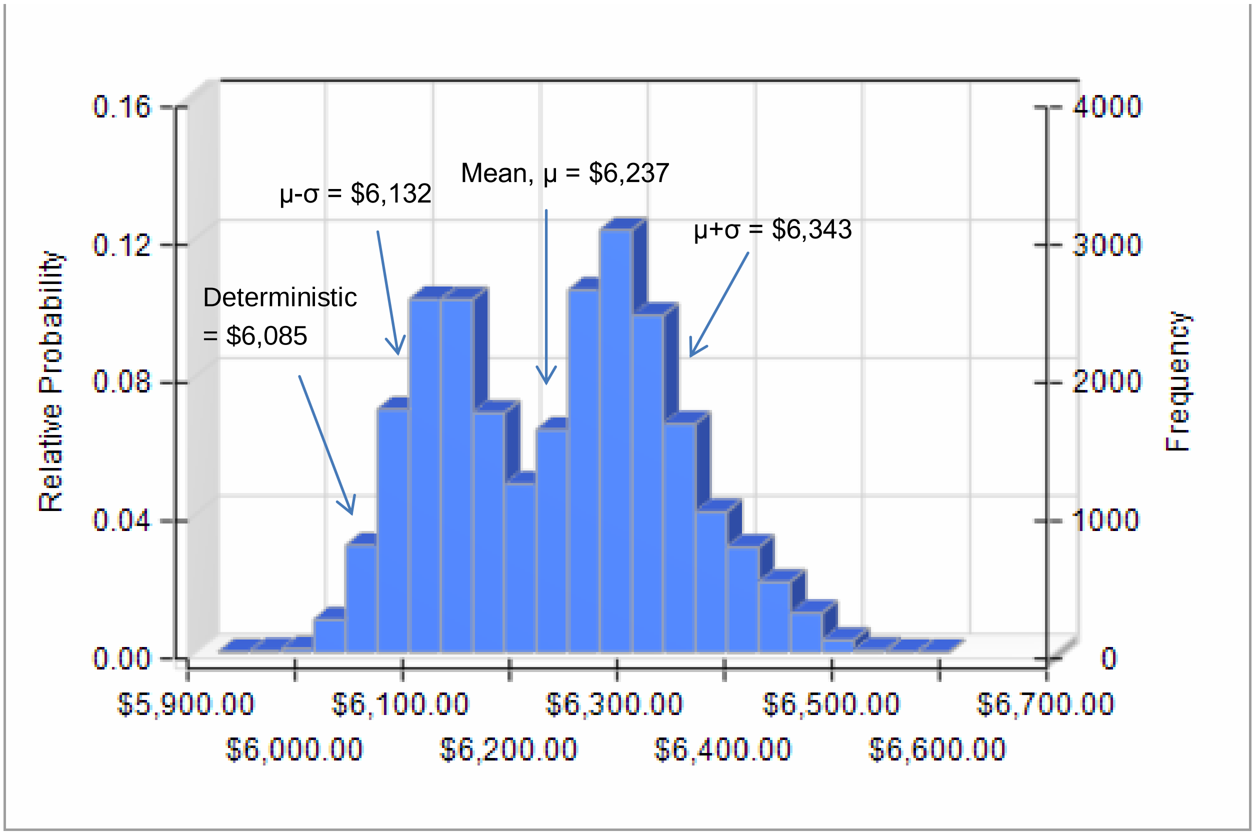


Figure 47 Status quo management – Impact of management on PV total cost ($ million) in year 35.

Least cost management

Under stochastic conditions, the estimated mean cumulative total cost over 35 years is statistically higher than the deterministic estimate. During the first ten years, the mean and deterministic cumulative total cost curves closely follow each other, and are both within the 90% CI. However, after year ten, the two curves diverge. The mean cumulative total cost over 35 years is $95 million compared to the deterministic cumulative total cost of $51 million (i.e., an increase of $44 million or about 87%). This comparative increase in the mean cumulative total cost in later years is likely because the decisions in the deterministic model had the luxury of perfect information (i.e., knowing exactly how effective management activities would be and how large or small LFA growth and spread would be). This allowed the deterministic model to tailor a single and unique policy for the given parameters, which minimized the objective. However, in the stochastic model, management decisions are set equal to the decisions in the deterministic least cost. Since the decisions in the stochastic case are fixed (and not optimized), the stochastic model lacks a mechanism to adjust decisions variables for changes in infestation and management. It is likely that the mean cumulative total cost than the deterministic cumulative total cost because of this lack of optimization. Even so, the least cost policy still ends up with a very low mean percent infestation (only 0.4%) in year 35. Furthermore, the sensitivity analysis, which did employ optimization, (see Sensitivity Analysis section) concluded that higher management costs would still warrant the management decision in the least cost scenario).

Unlike in the stochastic status quo model, lower than expected management effectiveness (not high effectiveness) shows a noticeable trend away from the mean and the deterministic results. The cumulative total cost over 35 years with low management effectiveness comes out to $202 million (i.e., three times higher than the deterministic value). That said, even with low management effectiveness, the least cost policy, still yields a lower total cost than any of the other scenarios. One possible explanation could be that reductions in management effectiveness lead to costs that accumulate overtime. That is, it's the opposite of the what happens in the status quo scenario. Reduced management effectiveness means it costs more to combat infestations, and infestations will be larger in the future, which would require additional expenditures to eliminate.

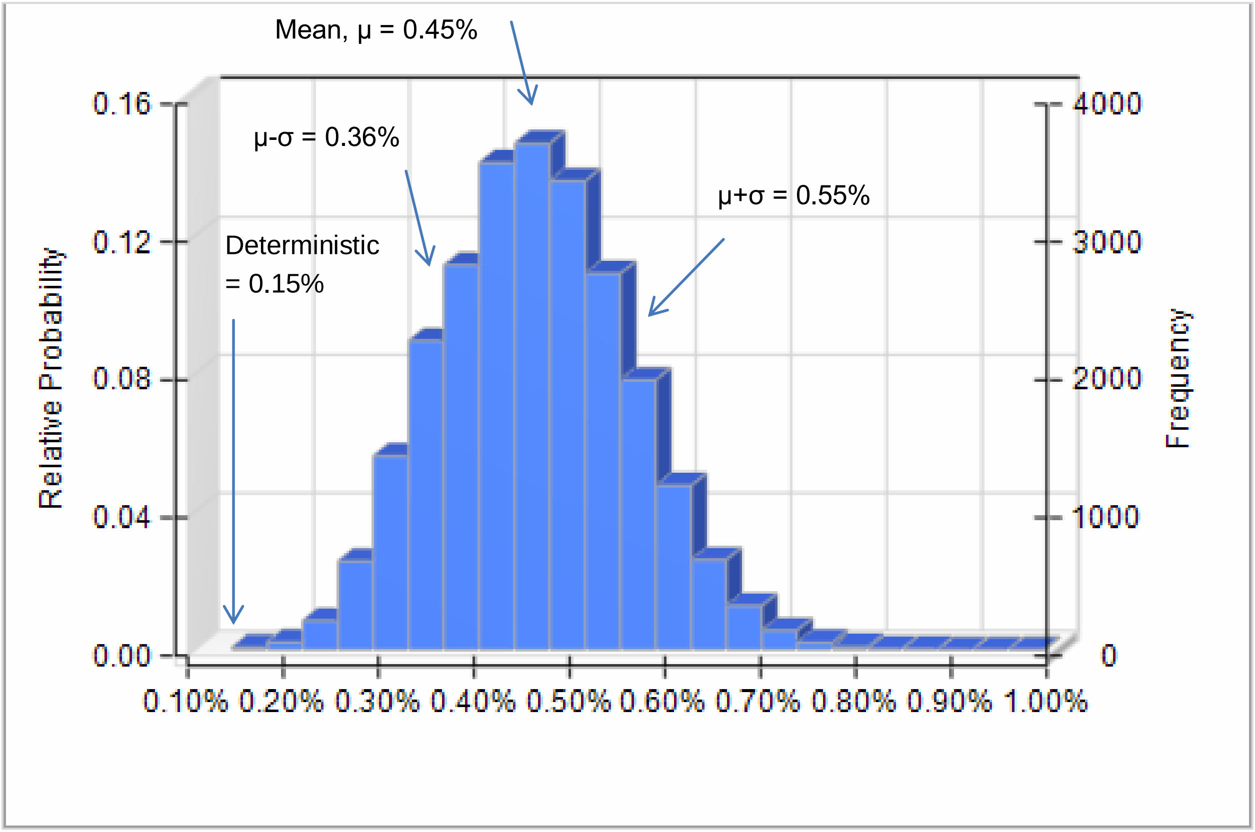


Figure 48 Least cost management – Impact of management on probable % LFA infestation in year 35.

Mean, μ = $95.7

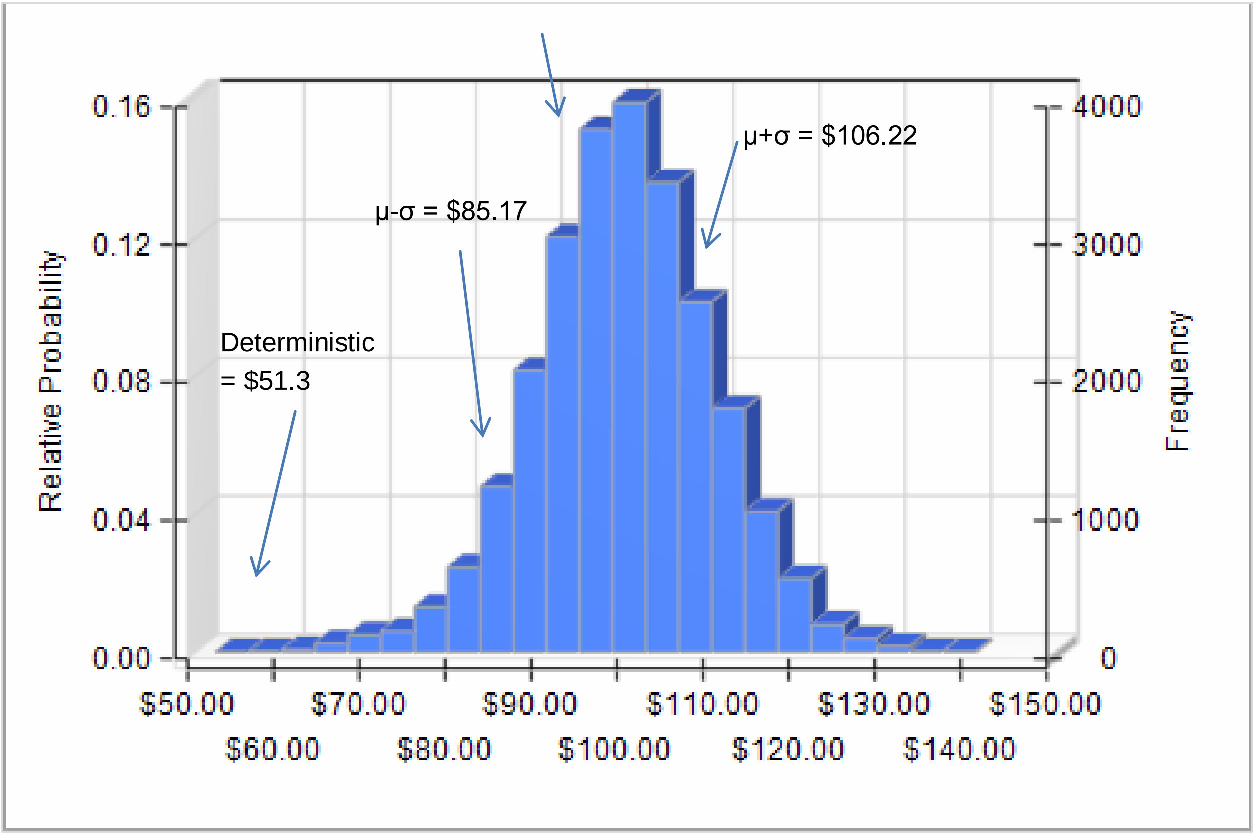


Figure 49 Least cost management – Impact of management on PV total cost ($ million) in year 35.

Comparison

When comparing the status quo to the least cost scenario, it is clear that the least cost policy leads to LFA infestation that is much lower than the status quo level. In year 35 of the least cost scenario, the percent of sites infested with LFA is brought below 1%. However, the percent of sites infested with LFA in year 35 of the status quo scenario levels out around 37% (see Table 28)

Table 28 Impact of management on LFA infestation and PV total cost ($ million)

	Measurement	Year 1		Year 10		Year 35	
		Least Cost	Status Quo	Least Cost	Status Quo	Least Cost	Status Quo
Cumulative PV total cost ($	Deterministic Value	$14.00	$15.40	$26.10	$1,364.60	$51.30	$6,085.20
	Lower 95th percentile	$13.60	$14.70	$24.70	$1,308.50	$78.90	$6,076.30
	Mean	$14.00	$15.40	$27.60	$1,360.90	$95.70	$6,237.50
	Upper 95th percentile	$14.40	$16.00	$32.20	$1,411.30	$111.60	$6,411.90
	Standard Deviation	$0.24	$0.40	$2.43	$32.47	$5.69	$105.58
	Coefficient of Variation	0.017	0.026	0.088	0.024	0.122	0.017
LFA Infestation	Deterministic Value	9.10%	19.50%	4.80%	32.70%	0.10%	34.10%
	Lower 95th percentile	8.00%	19.80%	3.50%	33.00%	0.30%	35.00%
	Mean	9.00%	21.10%	4.60%	34.60%	0.40%	36.80%
	Upper 95th percentile	9.90%	22.20%	5.80%	36.20%	0.60%	38.60%
	Standard Deviation	0.57%	0.72%	0.70%	0.99%	0.19%	1.07%
	Coefficient of Variation	0.063	0.034	0.152	0.029	0.205	0.029

Appendix D – Multiple objective analysis

Multi objective management

We evaluated two management objectives (minimize cost and minimize sting incidents) simultaneously to determine the efficient choices (Pareto frontier) for managing LFA and the social tradeoffs between the two objectives.

The minimax approach was used to minimize the maximum weighted percent deviation from the two objective goals as follows:

$$min: Q$$

subject to:

$$\frac{w_{cost} d_{cost}}{t_{cost}} \leq Q$$

$$\frac{w_{sting} d_{sting}}{t_{sting}} \leq Q$$

$$w_{sting} + w_{cost} = 1$$

where Q is the maximum weighted percent deviation, $w \in [0,1]$ are the relative weights, d are the deviation from the goals, t are the goals. The tradeoff curve approximates the set of possible Pareto optimal solutions, and is constructed by varying the relative weights. The goals t are the objective values (minimums) from the single objective optimization models.

The Pareto efficient outcomes for managing LFA with two management objectives: to reduce total costs (management expenditures and damages) and reduce human sting incidents is illustrated in Figure 50.

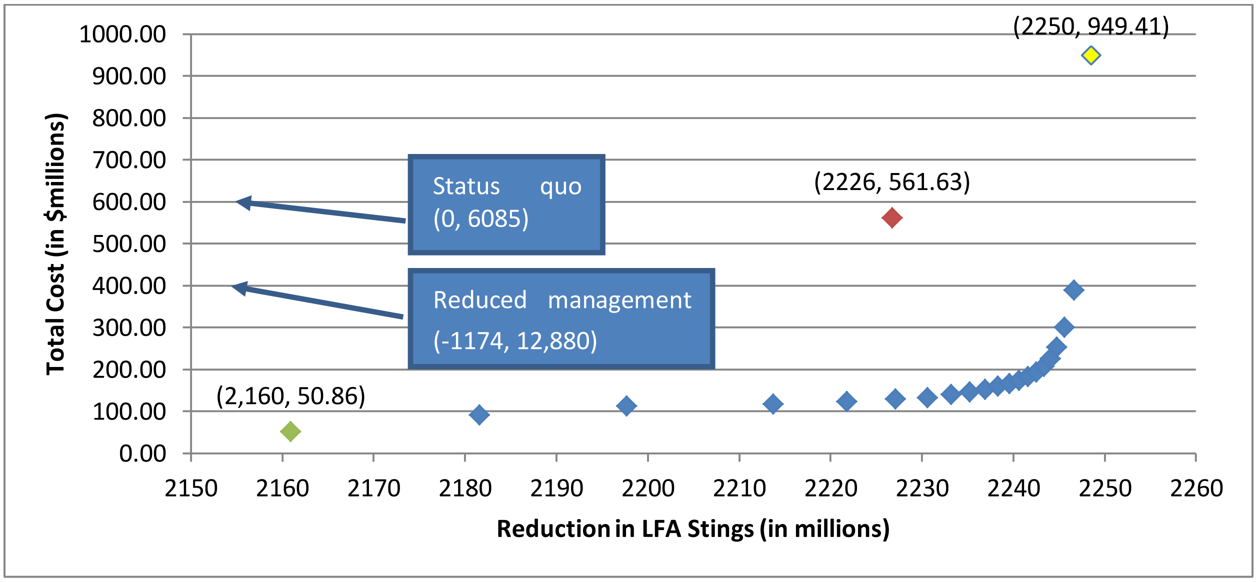


Figure 50 Tradeoff between increasing total cost and reducing human sting incidents.

In Figure 50 the Pareto frontier is indicated by the blue diamonds and the least cost outcome is a green diamond. The status quo and reduced management outcomes are indicated by blue boxes and inferior to the least cost outcome. The least sting outcome in yellow and the eradication outcome in red are inferior to other attainable points along the Pareto frontier. The current status quo course of action can be improved on though control actions to reduce infestations, reduce spread, and reduce stings.

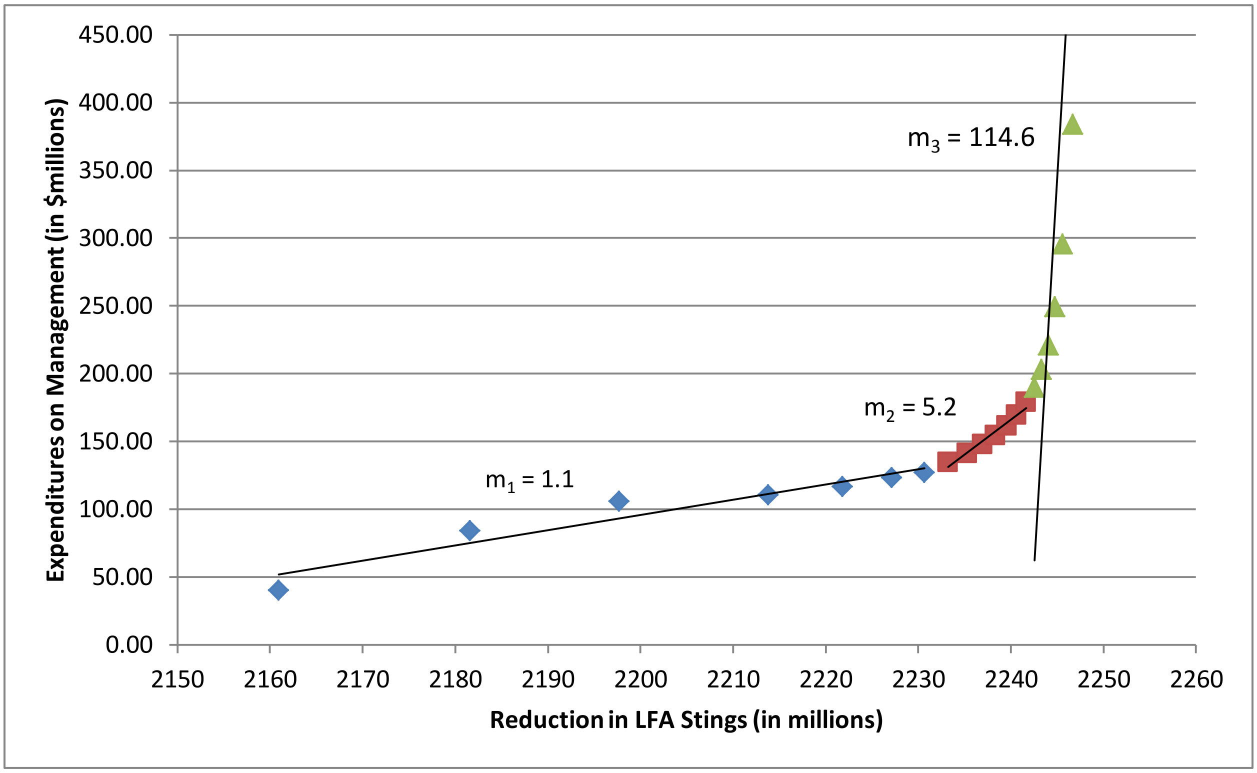


Figure 51 Average shadow cost of LFA stings

The average shadow cost of LFA human stings was estimated in terms of management expenditures at different segments of the trade-off curve. The average shadow cost of reducing LFA stings for the first segment of the tradeoff curve (the points between Run1 and Run7) is relatively low, m_1 = $1.1 per sting. In other words, LFA stings can initially be reduced at a relatively low cost. Overall, for the first segment of the tradeoff curve, about 70 million more LFA stings can be reduced by expending $82 million on additional management over the least-cost scenario (i.e., Run1) levels. The average shadow cost of reducing LFA stings for the second segment of the tradeoff curve (the points between Run8 and Run14) increases slightly (m_2 = $5.2) per sting as it becomes more difficult to eliminate the next units of LFA stings (i.e., management exhibits decreasing marginal returns). On this portion of the curve, 8 million more LFA stings can be eliminated by spending about $44 million more than Run7 levels of management. If policy makers determine a very high level of LFA sting abatement is necessary, then they should strive to achieve points along the last segment (the points between Run9 and Run21). The last segment has a very high average shadow cost of reducing LFA stings, m_3 = $114.6 per sting.

Status quo present value total cost is \$19.2 billion. Currently, 128,899 acres on the Big Island are infested with LFA, \$150,000 per acre.

To demonstrate the use of the tradeoff curve, we present an illustrative example Q_{equal} where the weights of LFA stings are Total Cost are equal (i.e., $w_{sting} = 0.5$, $w_{cost} = 0.5$). This scenario falls within the m_2 portion of the curve.

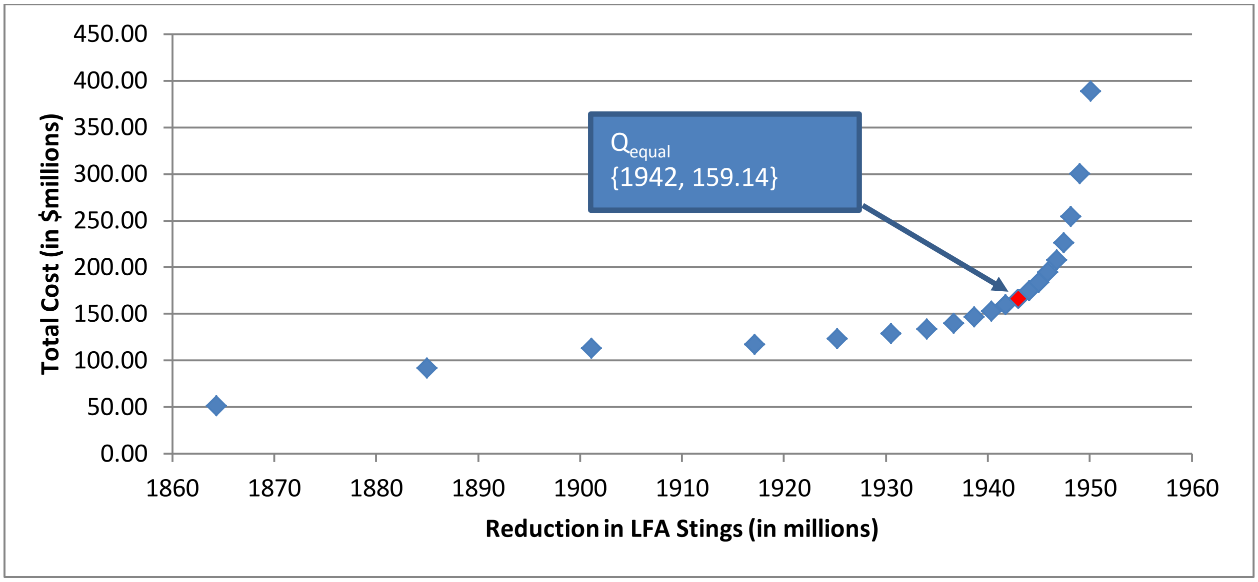


Figure 52 Location of Q_{equal} along the parteto frontier

Overall, this scenario incurs roughly \$159 million in LFA damage and management expenditures over the 35-year study period. Given the estimated initial 128,899 acres infested, this works out to about \$1235 per acre of initially infested area. This about three times more expensive than the least-stings scenario (\$435 per acre of initially infested area), and about five times less expensive compared to the least-sting scenario (\$5565 per acre of initially infested area). This additional management expenditure eliminates 77 million more LFA stings compared to the least-stings scenario, and only 10 million less LFA stings than the least-sting scenario.

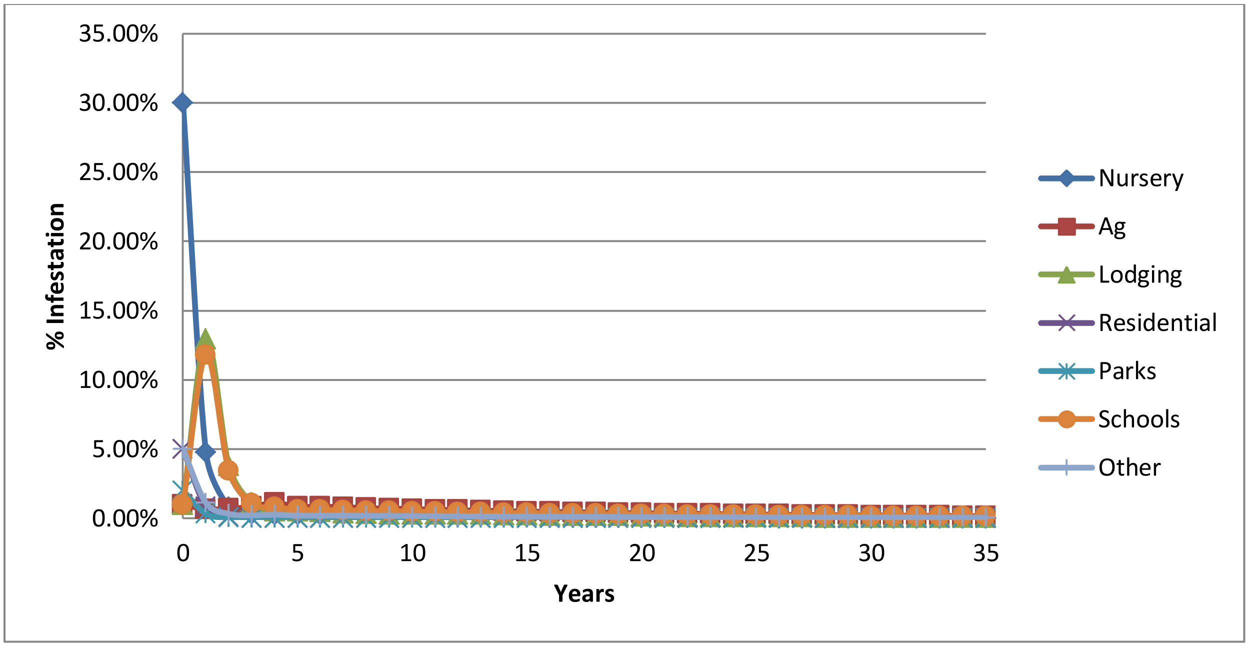


Figure 53 Annual percent infestation for the equal weight scenario

Like both the least cost and least sting scenarios, the equal weight scenario reduces the infestation size early on during the first few years (see Figure 53), and subsequently reaps the reward of reduced LFA stings and low total costs early on (see Figure 54 and Figure 55).

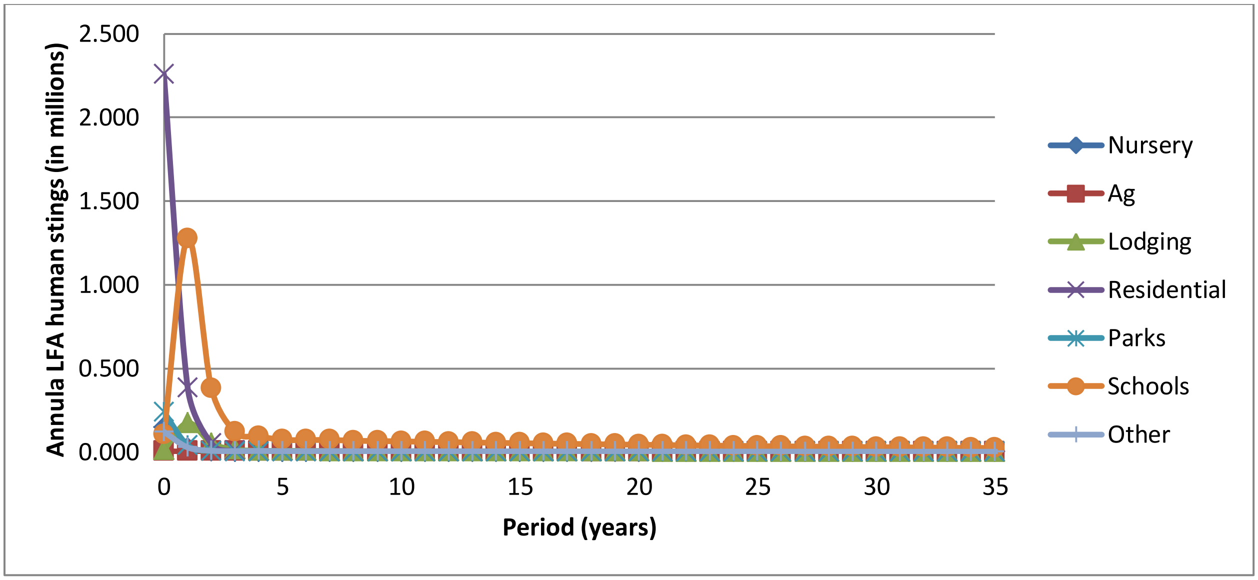


Figure 54 Annual LFA sting incidents for the equal weight scenario

Unlike other optimization scenarios, the school sector under the equal weight scenario incurs the highest total cost, followed by the lodging and other sector respectively. In these high cost sectors, the largest management expense comes from detection.

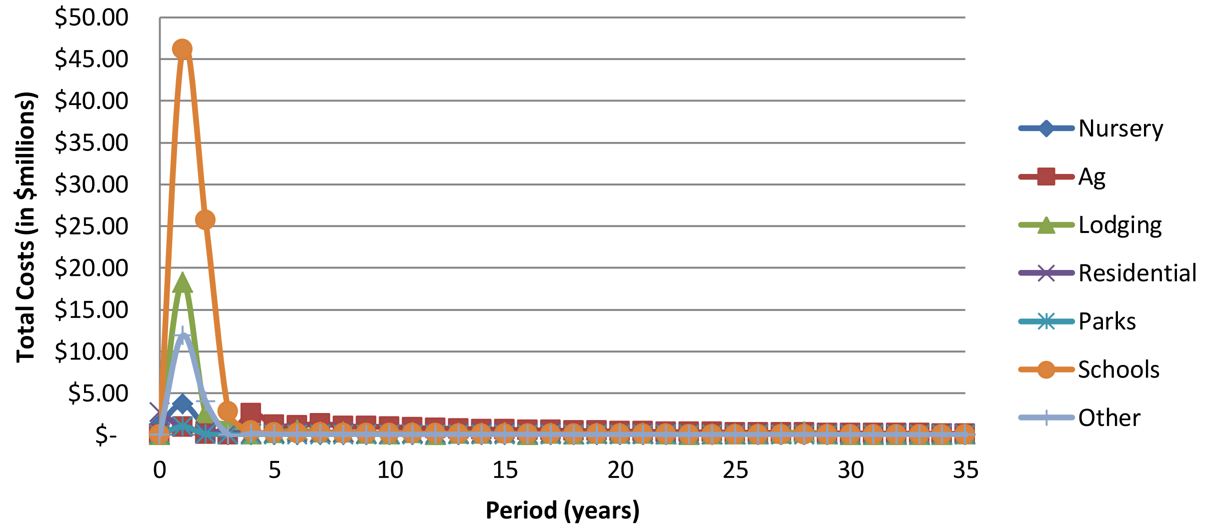


Figure 55 Annual total cost for the equal weight scenario

In this scenario, management costs are evenly distributed between management actions, unlike the least cost scenario, which was heavily mitigation oriented, and the least sting scenario, which was predominately detection and prevention, oriented (see Table 29).

Table 29 Equal weight scenario – Total cost over the duration of the study (in $ millions) and the total number of LFA stings (in millions)

Sector	**Cost and Damage Breakdown**					**LFA Human Stings**	
	Damage (% total)	**Mitigation Treatment** (% total)	**Detection** (% total)	**Prevention** (% total)	**PV Total Cost** ($ million)	**Reduction** (million)	**Reduction** (%)
Nursery	20.5%	0.8%	4.3%	74.5%	6.22	15.89	98.8%
Ag	0.0%	100.0%	0.0%	0.0%	22.36	6.93	98.4%
Lodging	1.3%	8.1%	44.8%	45.7%	28.18	371.75	99.9%
Residential	24.3%	1.0%	0.0%	74.8%	13.15	764.07	99.6%
Parks	0.0%	100.0%	0.0%	0.0%	1.23	485.47	99.9%
Schools	0.0%	31.1%	68.9%	0.0%	78.90	453.62	99.3%
Other	0.3%	18.2%	81.5%	0.0%	17.42	149.89	99.8%
Total	**2.9%**	**32.1%**	**48.6%**	**16.3%**	**167.46**	**2247.60**	**99.7%**

END of Appendices