Biological Control 100 (2016) 108–115

Contents lists available at ScienceDirect

Biological Control

journal homepage: www.elsevier.com/locate/ybcon

Cost effectiveness of biological control of invasive mole crickets in Florida pastures

Grace J. Mhina[a], Norman C. Leppla[b,*], Michael H. Thomas[a], Daniel Solís[a]

[a] Florida A&M University, College of Agriculture and Food Sciences, Division of Agricultural Sciences, Perry-Paige Building, Tallahassee, FL 32307, United States
[b] University of Florida, Institute of Food and Agricultural Sciences, Entomology and Nematology Department, 1881 Natural Area Drive, Gainesville, FL 32611, United States

HIGHLIGHTS

- Mole cricket biological control minimized Florida pasture losses due to this pest.
- The perpetual economic benefit had a benefit-cost ratio of 52:1.
- The highly successful mole cricket biological control required 34 years to complete.
- Mole cricket biological control is part of ongoing integrated pest management.
- Publicly funded mole cricket biological control was a prudent investment.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 13 April 2016
Revised 30 May 2016
Accepted 31 May 2016
Available online 2 June 2016

Keywords:
Mole cricket
Biological control
Economics

ABSTRACT

The Mole Cricket Biological Control Program (MCBCP) is a compelling example of successfully managing alien invasive pests that warrants formal analysis and documentation of its effectiveness and benefits relative to costs for cattlemen in the southeastern U.S. Three biological control agents that parasitize the short-winged mole cricket, *Neoscapteriscus abbreviatus* (Scudder); tawny mole cricket, *Neoscapteriscus vicinus* (Scudder); and southern mole cricket, *Neoscapteriscus borellii* (Giglio-Tos) (Orthoptera: Gryllotalpidae) were imported from the origin of the pests in South America, tested for non-target affects, and distributed widely in Florida. *Larra bicolor* F. (Hymenoptera: Crabronidae), a parasitoid of large nymph and adult mole crickets, was collected in Bolivia and established in Florida in 1988–89, and later in Georgia, Alabama, and Mississippi. Another parasitoid of large mole crickets, *Ormia depleta* (Wiedemann) (Diptera: Tachinidae), was introduced several times from Brazil during the early 1980s and released extensively. An entomopathogenic nematode discovered in Uruguay, *Steinernema scapterisci* (Nematoda: Rhabditida: Steinernematidae) reproduces within adult mole crickets, building up large populations that infect additional mole crickets and ultimately creates an epidemic. This very effective biological control agent was applied to pastures, turf farms, golf courses, athletic fields, and other mole cricket habitats across Florida after *in vitro* culture was developed and a commercial product, "Nematac® S," became available. During the 34 years of the MCBCP (1979–2012), about $8.7 million was spent on faculty salaries and operating costs and the overall annual savings in control costs was estimated to be $13.6 million; a first year benefit-cost ratio of 1.6:1. Applying a 3% social discount rate (perpetual benefit), the MCBCP will save cattle producers $453 million for a long-term benefit-cost ratio of 52:1.

* Corresponding author at: University of Florida, IFAS, Entomology and Nematology Department, 1881 Natural Area Drive, P.O. Box 110620, Gainesville, FL 32611-0620, United States.

E-mail address: ncleppla@ufl.edu (N.C. Leppla).

http://dx.doi.org/10.1016/j.biocontrol.2016.05.017
1049-9644/

1. Introduction

The Mole Cricket Biological Control Program (MCBCP) was established in 1979 within the University of Florida, Institute of Food and Agricultural Sciences (UF/IFAS), Entomology and Nematology Department to conduct research on controlling three species of alien invasive mole crickets that had been problem pests since about 1899–1925 (Frank and Leppla, 2009): the short-winged mole cricket, *Neoscapteriscus abbreviatus* (Scudder); tawny mole cricket, *Neoscapteriscus vicinus* (Scudder); and southern mole cricket, *Neoscapteriscus borellii* (Giglio-Tos) (Orthoptera: Gryllotalpidae) (Frank and Walker, 2006; Cadena-Castaneda, 2015). These pest mole crickets from South America became established in the southeastern U.S., the tawny and southern mole crickets becoming particularly widespread and occurring across the southern coastal plains from North Carolina west to Texas (Frank and Parkman, 1999) where they began to cause significant agricultural losses by mid-1900. Mole crickets severely damage pastures, other grassy areas, and vegetable crops by feeding primarily on roots and stems at night as they burrow underground. The MCBCP became necessary in 1979 because the U.S. Environmental Protection Agency withdrew registration of chlordane that had effectively controlled mole crickets in pastures. Other insecticides were tested in various formulations but all were less effective and more expensive. Consequently, UF/IFAS researchers conducted a classical biological control program involving foreign exploration for mole cricket natural enemies in South America. They also investigated mole cricket systematics, ecology, behavior, physiology, toxicology and pathology in an effort to discover alternative ways to control these pests (Frank and Parkman, 1999).

The MCBCP provided an opportunity to analyze the costs and benefits of using a combination of classical and augmentation biological control to successfully manage alien invasive pests (Frank and Parkman, 1999; Frank and Walker, 2006). Eventually, three biological control agents that parasitize *Neoscapteriscus* spp. mole crickets were imported, tested for non-target affects, and distributed widely in Florida (Frank and Walker, 2006). *Larra bicolor* F. (Hymenoptera: Crabronidae), a parasitoid of large nymph and adult mole crickets, was collected in Bolivia and established in Florida, Georgia, Alabama and Mississippi during the late 1980s (Frank et al., 2009). Another parasitoid of large mole crickets, *Ormia depleta* (Wiedemann) (Diptera: Tachinidae), was imported several times from Brazil during the early 1980s (Frank et al., 1996) and released extensively after rearing methods were developed (Wineriter and Walker, 1990). An entomopathogenic nematode discovered in Uruguay, *Steinernema scapterisci* Nguyen & Smart (Nematoda: Rhabditida: Steinernematidae), reproduces within adult mole crickets and builds up large populations that infect additional mole crickets (Georgis et al., 2006), ultimately creating an epidemic (Nguyen and Smart, 1990). This very effective biological control agent was applied to pastures, turf farms, golf courses, athletic fields, and other mole cricket habitats across Florida after *in vitro* culture was developed and Becker Underwood marketed the product, Nematac® S (Leppla et al., 2007). Establishment of these agents was verified and attempts were made to quantify their impacts on different mole cricket populations; however, the only long-term study was conducted in Gainesville, Florida (Frank and Walker, 2006) where >95% reduction occurred for both *N. vicinus* and *N. borellii*. In Central Florida pastures, applications of the nematode reduced mole cricket populations by 85% within three years (Leppla et al., 2007).

Many economic analyses have been completed for weed biological control projects (Culliney, 2005; McFadyen, 2008) but there are considerably fewer for insects (Voegele, 1989; Alvarez et al., 2016; Naranjo et al., 2015). Hill and Greathead (2000) included both weed and insect biological control in their analysis of 27 classical biological control programs worldwide that were conducted for 30–40 years and all but one had a benefit-cost ratio (BCR) greater than 1:1, indicating that successful programs are cost effective. Habeck et al. (1993) calculated the potential benefits of research on classical biological control using entomophagous insects and suggested that for projects costing $293,000 or $461,000 and lasting 4–7 years a return on investment of $62,000 or $97,000 per year, respectively, would assure a favorable BCR. This return was considered so low that many economically important pests would meet the necessary economic criterion for investing in classical biological control projects. Moreover, research on biological control reportedly is more cost effective than investments in chemical control (30:1 versus 5:1) and the overall BCR for classical biological control was estimated at 250:1 (Bale et al., 2008; Tisdell, 1990; van Driesche and Bellows, 1996). Biological control in general, including augmentation, has been highly cost effective with BCRs ranging from 3:1 to more than 100:1 (Van Driesche and Bellows, 1996).

Economic evaluation methods for insect biological control programs have lacked consistent methodology and often relied on cost approximations and producer interviews, resulting in highly variable BCRs, e.g., two-spotted spider mite, *Tetranychus urticae* (Koch) (24.4:1); wood wasp, *Sirex noctilio* (F.) (2.5:1); and white wax scale, *Ceroplastes destructor* Newstead (1.4:1). Comparing the geographical distribution of maize yields with release rates of *Cotesia flavipes* Cameron (Hymenoptera: Braconidae) over 20 years in Kenya, Africa, Kipkoech et al. (2006) estimated a BCR of 19:1 due to parasitism of the stem borer, *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae). In this study, reductions in yield were estimated using established pest density-yield loss functions rather than actual on-farm data. An analysis of the economic impact of *Diadegma semiclausum* (Hellen) introduced into Kenya for biological control of the diamondback moth, *Plutella xylostella* L., was conducted using both farmer interviews and measurements from farmer-managed fields (Macharia et al., 2005). The two sources of information yielded similar data. Variables analyzed included annual cabbage production and price, supply and demand, increased consumption, and economic surplus produced. Over 25 years, the gain was $28.3 million for a BCR of about 24:1. Mango producers in Benin, Africa were interviewed to determine plant production losses and positive impacts after the parasitic wasp *Gyranusoidea tebygi* Noyes (Hymenoptera: Encyrtidae) was introduced from India for biological control of the mango mealybug, *Rastrococcus invadens* Williams (Homoptera: Pseudococcidae). Interviewed mango producers gained an average of $328 per year, so by extrapolation the biological control program produced a yearly gain of $50 million for producers at all levels of mango production, estimated at $531 million over a period of 20 years. The total cost of the biological control program was estimated at $3.66 million, resulting in a BCR of 145:1 (Bokonon-Ganta et al., 2002).

Economic analyses of insect biological control projects are infrequently based on quantitative information. An exception is a detailed economic analysis of a 40-year effort to control the cassava mealybug, *Phenacoccus manihoti* Mat.-Ferr. (Homoptera: Pseudococcidae) in 27 African countries with its parasitoid *Apoanagyrus* (*Epidinocarsis*) *lopezi* De Santis (Hymenoptera: Encyrtidae) that indicated a combined annual loss reduction of $26 per hectare and the BCR of 199:1 to 297:1, depending on the situation in each country (Zeddies et al., 2000). A previous more conservative estimate for this ground-breaking biological control program yielded a BCR of 149:1 (Norgaard, 1988). In the U.S., growers of baby blue gum, *Eucalyptus pulverulenta* Sims, achieved BCRs ranging from 9:1 to 24:1 for biological control of the blue gum psyllid, *Ctenarytaina eucalypti* (Maskell) (Homoptera: Aphalaridae), with the parasitoid, *Psyllaephagus pilosus* Noyes (Hymenoptera: Encyrtidae)

(Dahlsten et al., 1998). These BCRs included only the savings in insecticide use and not higher foliage yields and other benefits. *Encarsia inaron* (Walker) (Hymenoptera: Aphelinidae) rapidly attained high levels of parasitism after being imported, mass reared and released throughout most of California for biological control of the alien invasive ash whitefly, *Siphoninus phillyreae* (Haliday) (Homoptera: Aleyrodidae) (Pickett et al., 1996). The ash whitefly biocontrol effort increased wholesale and retail values of trees and woody shrubs by $219,822,823 and $298,803,970, respectively. These values represented returns of $181 and $245 for every dollar spent by the California State Biological Control Program and the University of California. The BCR of 265:1 resulted from avoiding aesthetic damage to ash street trees alone (Jetter et al., 1997).

Millions of dollars were spent on the MCBCP during 34 years (1979–2012) and, while its success for cattle producers was clear, the economic return on this investment had not been quantified. In the 1980s, the annual cost of damage and control in Florida was roughly estimated at no less than $30 million (Walker, 1984). Between 1996 and 1999, about 300,000 hectares of pasture in South-Central Florida alone were damaged by mole crickets (Southern Exposure, 2004). The cumulative cost of this destruction was estimated to be $45 million with an additional $10 million needed for pasture renovation. Thus, statewide costs due to mole cricket infestations were estimated to be greater than $100 million per year (Frank and Parkman, 1999; Adjei et al., 2006). The objectives of this study were to: (1) Document the costs of developing and implementing the MCBCP, (2) Collect farm-level data on the hectares of Florida pasture infested by pest mole crickets, (3) Estimate the cost of controlling mole crickets in infested pastures before and after the MCBCP, and (4) Conduct a formal benefit-cost analysis to compare MCBCP funding with mole cricket control costs and quantify the economic benefits for cattle producers. The hypothesis was that the MCBCP significantly reduced the cost of preventing pest mole cricket damage to Florida pastures and, when these benefits were compared to the cost of the MCBCP, the BCR would be significantly greater than 1:1, a necessary condition for publicly funded projects (Mhina, 2013).

2. Materials and methods

A multi-stage framework was employed to collect and analyze all relevant information needed to evaluate the economic impact of the MCBCP. Initially, the costs were documented for its development and implementation by accessing available records and interviewing J.H. Frank, coordinator of the UF/IFAS Mole Cricket Research Program in 1985–2004 and N.C. Leppla, coordinator of the Mole Cricket State Program in 2001–2004. These two allied programs and subsequent work through 2012 were considered to be the MCBCP for the purpose of conducting this economic analysis. To collect primary data from cattle producers on the benefits of MCBCP, a survey was developed by an expert team of economists at Florida A&M University and widely distributed by the Florida Cattlemen's Association.[1]

2.1. Cost assessment

A thorough cost assessment was conducted of all work associated with the MCBCP during its 34 years of operation (1979–2012). These costs included operating funds derived from state appropriations, grants and other sources, and the compensation (salaries and benefits) of UF/IFAS faculty. The sources of operating funds, including the years and amounts received, were assembled accurately and adjusted to 2013 dollars for a total of $4,459,233 (Table 1), although not all of the resources were used entirely for the MCBCP. Included in these expenses were salaries for students, post-doctoral scientists, and temporary employees, and the cost of using multi-purpose vehicles and purchasing a limited amount of equipment and supplies. In addition to the MCBCP, faculty salaries supported a range of research, Cooperative Extension and teaching activities. To estimate the cost of faculty salaries, MCBCP records were used to identify participants and their ranks (Assistant, Associate or Full Professor) and determine the number of full time equivalents (FTEs) each devoted to the program annually and the number of years they participated. The FTEs × years × the average 2013 faculty salary for their rank yielded the adjusted salary each faculty member contributed to the MCBCP. Salaries were derived from University of Florida Employee Salaries for October 2013 (UF Salaries, 2013). The salaries for each faculty rank were an average of the salaries for 10 current members, excluding those without special assignments and associated higher salaries. Fringe benefits were derived from the University of Florida Fringe Benefits Pool for 2012–13 (UF Fringe Benefits, 2012–13). The resulting total was 31.7 faculty FTEs of effort at a cost of $3,371,990 for salaries and $782,303 for fringe benefits (Table 2). The cost of the MCBCP was the sum of operating costs and the cost of faculty salaries and fringe benefits ($8,613,526).

2.2. Benefit analysis

Benefits of the MCBCP were determined by collecting and analyzing farm-level data from Florida cattle producers who were members of the Florida Cattlemen's Association (FCA). This group was chosen for the survey because cattle production is the main agricultural sector affected by pest mole crickets in Florida and FCA members were considered representative of the industry. The FCA in collaboration with economists from Florida A&M University mailed 3800 surveys during October 2012 of which 200 were undeliverable and 15% unavoidably went to FCA members who were not cattle producers. After 2 months the survey was terminated with 580 completed and returned, only 3 containing information that was not usable. Thus, the adjusted response rate of useable surveys for this study was 19% (577/3030). The FCA did not allow the economists to have direct communication with its members, thus restricting survey follow-up and affecting the response rate. Nevertheless, a meta-analysis of response rates in academic studies showed that the rate in this study was within the expected range for social studies in agriculture (Baruch, 1999).

The survey was a modification of the Dillman 'tailored design method' (TDM) (Dillman, 2011) that enhances response rates from survey participants, yields unbiased answers and minimizes measurement error. The TDM is a set of procedures for conducting successful self-administered surveys that produce high quality information and high response rates. The survey included both closed and open-ended questions and was designed to collect three kinds of information: (1) Description of the cattle operation (location, size, number and type of cattle, etc.), (2) Hectares of pasture considered lost due to mole crickets, and (3) Cost of controlling mole crickets in infested pasture before and after the MCBCP. The survey was pretested for clarity by Florida Cooperative Extension faculty before being administered to the FCA members. The primary benefit of the MCBCP for cattle producers was cost savings computed by comparing past and current infestation levels and respective pest mole cricket control costs.

[1] The separation of tasks by team members in different institutions was done intentionally to avoid any conflict of interest and offer an unbiased economic analysis of the project. It is important to indicate that Florida A&M University was not part of the implementation of the MCBCP and did not receive financial support from the program.

Table 1
Estimated operational costs for the mole cricket biological control program, 1979–2012.

Source of funding[1]	MCBCP years	Amount ($)	Years of funding	Total ($)	Adjusted to 2013 ($)
Florida Legislature	1979–1991	60,000	13	780,000	2,794,533
USDA	1985–1998	15,000	13	195,000	246,260
USDA	1983–1986	45,000	3	135,000	316,621
FTGA	1987	20,000	1	20,000	41,126
UF/IFAS	1987–1991	10,000	4	40,000	82,252
Monsanto	1989	50,000	1	50,000	94,191
FTGA	1989	120,000	1	120,000	226,060
Golf course group	1989	40,000	1	40,000	75,353
Doral Resort	1990	5,000	1	5000	8936
UF/Ent. Nem. Dept.	1991–1996	35,000	5	17,500	30,014
USDA/APHIS/NBCI	1996	7500	2	15,000	22,332
Osceola Cat. A'ssn	1996	7500	1	7500	11,166
Golf Super. Ass'n.	1997	6000	1	6000	8732
Osceola County	1998	5000	1	5000	7165
USGA	1999	15,000	1	15,000	21,032
USGA	2001	10,000	1	10,000	13,190
Florida Ag. Comm.	2001	300,000	1	300,000	321,379
UF/IFAS Res. Dean	2001	15,000	1	15,000	19,731
FCA	2004	3000	1	3,000	3709
FCA	2004	5000	1	5,000	6183
UF/IFAS VP	2005[2]	75,000	1	75,000	80,344
USDA/NIFA/IPM	2010	27,000	1	27,000	28,924
Total				1,916,000	4,459,233

[1] Florida Turfgrass Association (FTGA), U.S. Golf Association (USGA), Florida Cattlemen's Association (FCA).
[2] Mole cricket research shifted from Florida to Puerto Rico for several years as required for T-STAR funding that is not included in the table.

Table 2
Mole cricket biological control program state-funded faculty effort and cost, 1979–2012.

Faculty member[1]	Rank	Years of participation (FTE/yr.)[2]	Total FTE per faculty member	2013 faculty salaries[3] ($)	Salary per faculty member ($)
1	Full	1 (0.5)	0.5	109,109	54,555
2	Asst.	1 (0.1)	0.1	84,155	8416
3	Assoc.	21 (0.1)	2.0	95,710	200,991
3	Full	7 (0.1)	0.7	109,109	76,376
		6 (0.5)	3.0		327,327
4	Full	12 (0.2)	2.4	109,109	261,862
		8 (0.1)	0.6		65,465
5	Full	7 (0.1)	0.8	109,109	87,287
6	Full	9 (0.1)	0.9	109,109	98,198
7	Asst.	6 (0.1)	0.7	84,155	58,909
8	Assoc.	6 (0.1)	0.7	95,710	66,997
9	Full	23 (0.1)	2.1	109,109	229,129
10	Full	1 (0.1)	0.1	109,109	10,991
11	Full	4 (0.1)	0.3	109,109	32,722
12	Full	2 (0.1)	0.2	109,109	21,822
13	Full	20 (0.1)	1.8	109,109	196,396
14	Full	8 (0.1)	0.8	109,109	87,287
15	Full	9 (0.6)	5.4		589,189
		8 (0.4)	3.6	109,109	392,792
16	Assoc.	3 (0.1)	0.3	95,710	28,713
17	Assoc.	9 (0.3)	2.7	95,710	258,417
18	Full	10 (0.2)	2.0	109,109	218,218
Total					
FTE & salaries			31.7		3,371,990
Fringe benefits 23.2%					782,303
Salaries & benefits					4,154,293

[1] University of Florida, Entomology and Nematology Department faculty participation in the mole cricket biological control program based on university records and recollections of J.H. Frank and N.C. Leppla. Program coordinators: Carl S. Barfield (1979), Thomas J. Walker (1979–85), and J. Howard Frank (1985–94).
[2] FTE = full time equivalents.
[3] Salaries were derived from University of Florida Employee Salaries for October 2013 (UF Salaries, 2013) and fringe benefits were from the University of Florida Fringe Benefits Pool: 2012–13 (UF Fringe Benefits, 2012–13).

The number of hectares of pasture, type of operation (beef cattle production, cattle finishing, cow-calf, dairy) and other important characteristics naturally differed between North, Central and South Florida, so the analysis was divided into three regions: Region 1, North Florida, 35 counties (Alachua, Baker, Bay, Bradford, Calhoun, Clay, Columbia, Dixie, Duval, Escambia, Flagler, Gadsden, Gilchrist, Gulf, Franklin, Hamilton, Holmes, Jackson, Jefferson, Lafayette, Leon, Levy, Liberty, Madison, Nassau, Okaloosa, Putnam, Santa Rosa, St. Johns, Suwannee, Taylor, Union, Wakulla, Walton, and Washington); Region 2, Central Florida, 21 counties (Brevard, Citrus, Desoto, Hardee, Hernando, Highlands, Hillsborough, Indian River, Manatee, Marion, Okeechobee, Orange, Osceola, Pasco, Pinellas, Polk, Sarasota, Seminole, St. Lucie, Sumter, Volusia); and Region 3, South Florida, 10 counties (Broward, Charlotte, Collier, Dade, Glades, Hendry, Lee, Martin, Monroe, and Palm Beach). Based on data from the National Agriculture Statistics Service, Regions 1, 2

Table 3
Estimated number of hectares of pasture infested by mole crickets in North, Central and South Florida.

Categories of infested pasture reported by producers[1]	(I_p) Infested pasture reported by producers (%)	(R_i) Producers reporting infested pasture (%)	(P_i) Proportion infested pasture (Ip^*R_i)	(H_i) Estimated hectares infested pasture ($H_t^*P_i$)
North Florida (428,522 total hectares, H_t)				
<10%	14	49	0.07	29,997
10–25%	62	40	0.25	107,131
26–50%	24	11	0.03	12,856
>50%	0	0	0	0
Total	100	100	0.35	149,984
Central Florida (1,227,290 total hectares, H_t)				
<10%	5	39	0.02	24,546
10–25%	38	40	0.15	184,094
26–50%	43	15	0.06	73,637
>50%	14	6	0.01	12,273
Total	100	100	0.24	294,550
South Florida (339,976 total hectares, H_t)				
<10%	40	40	0.16	54,396
10–25%	53	40	0.21	71,395
26–50%	7	20	0.01	3400
>50%	0	0	0	0
Total	100	100	0.38	129,191

[1] Producers responding in North Florida (n = 58), Central Florida (n = 64), and South Florida (n = 8).

and 3, respectively, contained 428,522; 1,227,290; and 339,976 hectares of pasture (USDA, 2010). The number of hectares of pasture considered infested by mole crickets in each region was estimated in 2 steps: (1) The proportion of pasture infested in each region was calculated by multiplying the percentage of pasture producers reported as infested by the percentage of producers who reported infested pasture, and (2) The proportion of infested pasture was multiplied by the total hectares of pasture in the region (Table 3). The producers were asked to report the percentage of infested pasture in categories of <10%, 10–25%, 26–50%, and >50%.

The economic impact of MCBCP was calculated first by multiplying the estimated total regional hectares of pasture lost (from Table 3) by the percentage of producers reporting that the mole cricket problem ended after MCBCP, continued, began after MCBCP, or never occurred (Table 4). Mole cricket control costs before and after MCBCP were reported for these categories and used to calculate the savings. The difference between the pre- and post-MCBCP costs was assumed to be the savings obtained by not having to control pest mole crickets. The total savings for each category was calculated by multiplying the savings per hectare by the number of hectares of lost pasture. The sum of the savings for the categories provided an estimate of the regional cost savings due to MCBCP. The pre-project control costs were estimated in 1983 U.S. dollars and later discounted to 2013 U.S. dollar values using the U.S. Department of Labor, Bureau of Labor Statistics, CPI Inflation Calculator (USDL, 2013).

The estimated regional hectares of pasture infested with mole crickets:

$$I_p * R_i = P_i; P_i * H_t = H_i$$

where I_p = percentage of infested pasture reported by producers; R_i = percentage of producers reporting lost pasture; $I_p{}^*R_i = P_i$ proportion of lost pasture; H_t = total hectares of pasture in the

Table 4
Cattle producer reported annual savings due to the mole cricket biological control project in North, Central and South Florida.

Mole cricket status[1]	(R_{ia}) Producers responding (%)[2]	(H_{ia}) Hectares infested pasture ($R_{ia}{}^*H_i$)[3]	Annual Pre-MCBCP control cost/ha[4]	Annual Post-MCBCP control cost/ha[5]	(S_h) Control cost savings/ha	(S_t) Total savings ($H_{ia}{}^*S_h$)
North Florida (149,984 total infested hectares, H_i)						
Ended	23	34,496	$132.37	0	$132.37	$4,566,236
Continued	18	26,997	$26.95	$42.61	($15.66)	($422,773)
Began	5	7499	$132.37	$123.50	$8.87	$66,516
Insignificant	54	80,991	–	–	–	–
Total savings						$4,209,979
Central Florida (294,550 total infested hectares, H_i)						
Ended	19	55,965	$92.30	0	$92.30	$5,165,570
Continued	23	67,747	$46.88	$20.35	$26.53	$1,797,328
Began	3	14,728	$92.30	$63.60	$28.70	$422,694
Insignificant	55	–	–	–	–	–
Total savings						$7,385,592
South Florida (129,191 total infested hectares, H_i)						
Ended	12	15,503	$68.12	0	$68.12	$1,056,064
Continued	18	23,254	$68.12	$26.92	$41.20	$958,065
Began	0	–	–	–	–	–
Insignificant	70	–	–	–	–	–
Total						$2,014,129

[1] Ended, continued, or began after the MCBCP or was insignificant and did not require control.
[2] Producers responding in North Florida (n = 219), Central Florida (n = 253), and South Florida (n = 50).
[3] H_{ia} = % producers responding x total hectares infested (from Table 3).
[4] Pre-MCBCP control cost per hectare is producer reported.
[5] Post-MCBCP control cost per hectare is producer reported.

region; $H_t{}^*P_i = H_i$, estimated hectares of infested pasture in the region (Table 3).

The estimated cost savings due to the MCBCP:

$$R_{ia} * H_i \text{ (from Table 3)} = H_{ia}; H_{ia} * S_h = S_t$$

where R_{ia} = percentage of producers reporting infestation levels after MCBCP; H_{ia} = estimated hectares of lost pasture in the region; S_h = control cost savings per hectare; $H_{ia}{}^*S_h = S_t$, total savings for the region.

3. Results

3.1. Pasture infested by mole crickets

The 130 responding cattlemen estimated the percentage of pasture infested by mole crickets in the following categories: <10%, 10–25%, 26–50% or >50% (Table 3). For North Florida, 49% of the cattlemen reported that 14% of their pasture had <10% damage, 40% indicated that 62% of their pasture had 10–25%, 11% stated that 24% had 26–50%, and none experienced >50% damage. The estimated number of hectares of infested pasture in the first 3 categories was 29,997, 107,131, and 12,856, respectively. Central and South Florida also had predominantly 10–25% infested pasture. North Florida had a total of 428,522 hectares of pasture and 149,984 (35%) were reported by the cattlemen as being infested by mole crickets. Compared with North Florida, Central Florida contained almost 3 times as many hectares of pasture, 1,227,290 of which 294,550 hectares (24%) were infested. The pattern of infested pasture in South Florida was similar to the other 2 regions with 129,191 of 339,976 hectares (38%) infested by mole crickets. A total of 573,725 hectares of the 1,995,788 hectares of Florida pasture (29.0%) was reported infested for all three regions (Table 5).

3.2. Savings due to the MCBCP

The goal of the MCBCP was to reduce pasture losses due to pest mole crickets so that remaining control costs could be minimized and damaged pasture recovered for livestock production. The cost of controlling mole crickets was approximated by determining the number of cattlemen who no longer had a mole cricket problem after the MCBCP, continued to have a problem, had a problem begin after the MCBCP, or never had a significant mole cricket problem (Table 4). The respective percentages in the 4 categories for North Florida were 23, 18, 5, and 54%. About half of the cattlemen in Central and South Florida reported that the mole cricket did not require control to protect their pastures. The cattlemen were asked to estimate their annual mole cricket control costs per hectare before and after the MCBCP. The maximum pre-MCBCP inflation adjusted-cost (USDL, 2013) for mole cricket control occurred in North Florida ($132.37 per hectare); whereas, Central Florida had the highest cost after the program ($63.60 per hectare). A significant number of cattle producers in North Florida (18%) actually experienced an increase in mole cricket control costs from $26.95 to $42.61 per hectare. Overall, however, the producers reported annual savings due to the MCBCP of $4,209,979; $7,385,592; and $2,041,129 for North, Central and South Florida, respectively (Table 4).

4. Discussion

4.1. Benefit-cost ratio (BCR) for the MCBCP

Regardless of whether the mole cricket problem ended or continued with much less damage to Florida pastures, the total annual estimated post-MCBCP savings in control costs was $13,609,698 (Table 5). Considering only grant and agreement funding, the initial annual BCR for the MCBCP was 3:1, $13.6 million savings in control costs divided by $4.5 million in investments (Table 1). The BCR was reduced to 1.6:1 ($13.6 million/$8.6 million) if the proportions of faculty salaries devoted to the project (Table 2) were included in the calculation. Because the two parasitoids were established and the nematode reproduces in the host mole crickets, long-term biological control has been achieved. Thus, over the 10 years post-MCBCP the cattle producers will save $136 million, a BCR of 15.6:1. Economists commonly use a social discount rate to estimate permanent benefits resulting from an investment. Dahlsten et al. (1998), for example, used 8% to calculate the long-term benefits of the blue gum psyllid biological control project. Applying the current rate of 3% (Boardman et al., 2010), the perpetual benefit of the MCBCP is $453 million ($13.6 million/.03), a BCR of 52:1. This ratio is an economic indicator that summarizes the overall benefit provided by minimizing the statewide cost of mole cricket control. The 52:1 BCR is conservative since the number of hectares of pasture being damaged by mole crickets and associated control costs were increasing prior to the MCBCP.

4.2. Long-term benefits of the MCBCP

The continuous cost of managing mole crickets in Florida pastures, as well as golf courses, turf farms, athletic fields, residential lawns, and other areas infested by mole crickets would have been much greater if the Florida Legislature and other organizations had not funded the MCBCP. Nearly 2 million hectares potentially would have become infested and damaged at some level as the pest mole crickets spread throughout Florida (Table 5). Fortunately, due to the MCBCP and other mole cricket pest management practices, infested pasture was limited to about 573,725 hectares, 29% of the hectares that could have become infested. The annual cost of controlling these pests could have exceeded $18 million.

In addition to saving control costs, cattle producers continue to receive the benefits of increased pasture quantity and quality (Leppla et al., 2007). The South Florida producers estimated that

Table 5
Estimated annual savings in 2013 after the mole cricket biological control program (MCBCP).

Region	No. hectares of pasture[1] (H_t)	No. hectares of pasture infested (H_i)	Pasture infested (%)	Pre-MCBCP annual control cost[2]	Post-MCBCP annual control cost[3]	Post-MCBCP annual savings (S_t)
North Florida	428,522	149,984	35.0	$6,286,448	$2,076,469	$4,209,979
Central Florida	1,227,290	294,550	24.0	$9,700,943	$2,315,353	$7,385,592
South Florida	339,976	129,191	38.0	$2,640,127	$625,998	$2,014,129
Total	1,995,788	573,725	29.0	$18,627,518	$5,017,820	$13,609,698

[1] Number of hectares of Florida pastures (USDA, 2010).
[2] The pre-MCBCP annual cost is the number of infested hectares, H_{ia}, (from Table 4) x the pre-MCBCP cost for each condition (problem ended, continued or occurred), totaled.
[3] The post-MCBCP annual cost is the number of infested hectares, H_{ia}, (from Table 4) x the post-MCBCP cost for each condition (problem ended, continued or occurred), totaled.

hay and forage losses due to mole cricket damage cost nearly \$45 million annually plus an additional \$10 million for pasture renovation (Adjei et al., 2003). According to our analysis, about 105,964 (34,496 + 55,965 + 15,503) of the 573,725 hectares (18.5%) of pasture reportedly infested in North, Central and South Florida (149,984 + 294,550 + 129,191) have been recovered due to the problem ending after the MCBCP (Table 4). Even if mole cricket problems continued, control costs were reduced on another 117,998 hectares (26,997 + 67,747 + 23,254), an additional 20.6%. Average cattle stocking reductions were 4%, 11%, and 7% on pastures in North, Central and South Florida, respectively, prior to the MCBCP. At least 10% of the producers also reacted to mole cricket infestations by increasing supplemental feeding of cattle and by renovating pastures or taking them out of production and converting the land to other uses. Although, the primary action prior to the MCBCP was to maintain productive pastures by applying expensive insecticides, typically broadcast baits, as reported by 35%, 51%, and 46% of producers in the three respective regions. Of the respective producers in North, Central and South Florida, 79%, 67%, and 86% relied on some kind of chemical control of mole crickets. It is necessary to maintain healthy pastures because most producers are committed long-term to the cattle business: <10 years 11.2%, 10–20 years 22.7%, 21–40 years 33.3%, 41–60 years 22.1%, and >61 years 10.7% (n = 525). These producers reportedly earn 60–70% of their annual income from cattle production.

4.3. Additional benefits of the MCBCP

Biological control projects require many years to develop during which they have both direct and indirect economic benefits. This project added \$4,154,293 in operating funds and salaries for students and technicians who otherwise might not have been supported (Table 1). Initially, the MCBCP was funded by a 2013-adjusted \$2,794,533 appropriation from the Florida Legislature, likely prompted by influential Florida cattlemen. Significant investments were added over the years by the USDA, Florida Turfgrass Association, University of Florida, and various stakeholders. Due to encouragement by a leading cattle producer, in 2001 the Florida Commissioner of Agriculture provided \$300,000 to develop and widely apply *S. scapterisci*. Use of the nematode for pest mole cricket biological control was patented by the University of Florida and licensed exclusively to Becker Underwood who marketed it as Nematac® S. The product was sold for use not only on pastures but also for athletic fields, golf courses, turfgrass farms, private landscapes, and other locations infested by mole crickets. Another indirect benefit of the MCBCP was participation by many University of Florida faculty members who were not employed specifically for this purpose (Table 2). Publicly funded faculty salaries and fringe benefits provided a range of research, Cooperative Extension and teaching functions in addition to the MCBCP. At least 19 faculty members contributed their expertise part-time over 34 years at an adjusted cost of \$4,154,293.

4.4. Expectations for publicly funded research

Public funding was provided for research on mole crickets and their natural enemies with the expectation that cost effective biological control would be achieved. Through foreign exploration in South America, effective biological control agents were discovered, imported, propagated, tested for host specificity, released throughout Florida, and monitored for establishment. The *Larra* wasp and Brazilian red-eyed fly were widely-distributed and established throughout much of the state by UF/IFAS faculty, staff and students (Frank and Walker, 2006; Frank et al., 2009); whereas, the nematode was produced commercially and applied both by cattle producers as a "biopesticide" and by UF/IFAS personnel in extensive inoculative releases. Near Gainesville, the three biological control agents were effective in parasitizing *Neoscapteriscus* spp. mole crickets, and populations of *N. borellii* and *N. vicinus* were reduced to <5% of the pre-release baseline numbers (Frank and Walker, 2006). To obtain additional quantitative data on the impact of the nematode, a large field experiment was conducted in Polk County but the highly mobile infected mole cricket adults unexpectedly contaminated the control plots (Adjei et al., 2006). This mobility proved to be an advantage, however, because cattle producers based the price they were willing to pay for nematodes on the general cost of a fertilizer application, about \$62 per hectare. Becker Underwood charged \$200 for one billion nematodes, the recommended broadcast application rate per hectare being about 2.5 billion. At a cost of \$500 for 2.5 billion infective juveniles per hectare, it would not have been feasible to use the nematodes. However, since the nematodes quickly spread across a pasture, they were applied in widely spaced strips that covered 0.125 hectares at the rate of 312 million per hectare (Adjei et al., 2006). The efficacy, availability and cost requirements for the cattle producers to use the nematode were met and, combined with the wasp and fly, provided the expected biological control of the pest mole crickets.

4.5. Current mole cricket control in Florida

The MCBCP ended in 2012 but mole cricket biological control has been sustained as part of an integrated pest management system that includes damage thresholds and a set of management options based on cultural, biological and chemical control (Kerr et al., 2014). Preventative cultural control tactics, include selecting tolerant grass cultivars, altering soil moisture, limiting attractive lighting, determining the timing and depth of tillage, enhancing plant health, and maintaining pest management records. Mole cricket biological control no longer includes the introduction of new agents and associated augmentation, rather it has become conservation of parasitoids and predators, which includes planting nectar sources, such as *Pentas lanceolata* (Forssk.) Deflers, *Chamaechrista fasciculata* (Michx.) Greene, *or Spermacoce verticillata* L., even though it is listed as a Category II Invasive Plant Species by the Florida Exotic Pest Plant Council (FEPPC, 2015). Chemical control in pastures is recommended only for eliminating local outbreaks by selectively using registered insecticides containing *Beauveria bassiana*, pyrethrins, or carbaryl. Mole crickets periodically reinvade pastures following pesticide applications, flooding, disking, and other disturbances that disrupt biological control by eliminating the host. The reinvading pests can reach outbreak levels before the biological control agents reestablish and provide suppression. Biological control will never be restored in pastures where pesticides are used continuously. Currently, augmentation is impossible because the parasitoids are not mass-produced and the nematode is no longer available commercially. An attempt was been made by Florida Cooperative Extension during the fall 2010 mole cricket season to boost sales of Nematac® S by completing a series of applications in cooperation with cattle producers in North Florida. However, by that time *S. scapterisci* had spread throughout most of Florida and consequently there was no longer a sufficient market for the nematode product. The publicly funded research and Extension activities, along with nematode production and marketing by Becker Underwood, enabled the MCBCP to be highly successful. The nematode has been detected commonly in infected mole crickets and the soil by means of an immunoassay (L. Duncan, personal communication). *Larra bicolor* has continued to extend its distribution across Florida (Frank et al., 2009), parasitizing mole crickets within 200 m of its primary nectar source, shrubby false buttonweed, *S. verticillata* L. (Portman et al., 2010).

The Brazilian red-eyed fly is widely distributed in peninsular Florida southward from Alachua County. Due to prudent investments made in the MCBCP, parasitized and infected mole crickets continually reestablish the three biological control agents in infested pastures as pest populations build and there is no recurring cost to the cattle producers for this ecological service.

Acknowledgments

We thank Dr. J.H. Frank (University of Florida) for providing detailed information about the mole cricket biological control program and helping to develop the manuscript. This paper could not have been written without his many contributions. Dr. J.R. Nechols (Kansas State University) thoroughly reviewed the manuscript and contributed editorial assistance. Dr. D. Harding (Florida Fishing and Wildlife Commission) assisted with the economic analysis. We also thank USDA, APHIS and the Center for Biological Control at Florida A&M University for sponsoring this research. Post-MCBCP funding was provided by USDA, NIFA and the Southern IPM Center. We gratefully acknowledge the Florida Cattlemen's Association for distributing the survey to their members and C.R. Kerr (University of Florida) for critically reviewing the manuscript.

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