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Research

*e-Xtra**

An Integrated Pest Management Program Outperforms Conventional Practices for Tomato (*Solanum lycopersicum*) in Cambodia

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Abstract

For several years, pest management in tomato production in Cambodia has generally focused on the use of synthetic pesticides. We compared conventional pest management (farmers' traditional practices) with an integrated pest management (IPM) program on 12 farms in the northwestern part of Cambodia. The IPM program combined cultural, biological, and chemical practices. We found that IPM practices reduced aphid damage by 46%, and diseases such as Fusarium wilt and damping-off were substantially reduced. Our results indicate that the IPM package increased tomato yield and income by an average of 23 and 34%, respectively, compared with conventional practices during both dry and rainy seasons.

Keywords: arthropods, biological control, chemical control, cultural control, disease

Tomato (*Solanum lycopersicum* L.) (Solanaceae) is one of the most important vegetables in Cambodia. The total area cultivated is 1,065 ha and represents a source of employment for more than 1,400 families in rural and suburban areas (World Bank Group 2015). Few Cambodian provinces supply vegetable markets; it appears that only six provinces produce 30% of consumed vegetables. The other 70% are imported from Vietnam (Eliste and Zorya 2015). Two main varieties of tomato, Neang Pich and Neang Tamm, are cultivated in Cambodia (Mund 2011), but the yield is severely affected by insect pests and pathogens, causing losses of 40% (Schreinemachers et al. 2015). Despite the importance of tomato and its severe pest problems, the need to establish integrated pest management (IPM) programs has received little attention in Cambodia. This lack of attention has resulted in the overuse of pesticides, increased pesticide resistance, reduction of natural enemies, and growing threats to the environment and human health (Mund 2011). Adopting an IPM approach that integrates cultural, biological, and chemical practices may increase tomato yield while reducing dependence on harmful pesticides (Mund 2011).

Numerous pests can cause economic losses in tomato crops; however, little is known about tomato pests in Cambodia. Tomato crops in Cambodia can be affected by pest species reported in other countries in Southeast Asia. For example, many studies report that several arthropods cause damage to the foliage and fruit, including spider mites (*Tetranychus urticae* Koch), and insects such as armyworms (*Spodoptera exigua* (Hübner) and *S. litura* (Fabricius), leafminer (*Liriomyza* sp.), tomato budworm (*Helicoverpa armigera* (Hübner)), whiteflies (e.g., *Bemisia tabaci* (Gennadius)), aphids (*Myzus persicae* Sulzer and *Macrosiphum euphorbiae* Thomas), and thrips (e.g., *Thrips palmi* Karny) (McDougall et al. 2013; Sen 2016). Bacteria, fungi, and viruses can also cause significant damage in tomato; for example, bacterial wilt (*Ralstonia pseudosolanacearum*) (Klass et al. 2020), Fusarium wilt (*Fusarium oxysporum* f. sp. *lycopersici*), powdery mildew (*Sphaerotheca fuliginea*), and late blight (*Phytophthora infestans*) are important diseases. The most abundant viruses in tomato crops are tomato yellow leaf curl viruses (Tolin and Fayad 2016; Yule et al. 2019). Currently, insect pests are managed using synthetic pesticides such as imidacloprid, pyrethroids, and organophosphates and effective fungicides are lacking, except for late blight management. These pesticides are often misused, resulting in added cost to the farmer, inadequate pest control,

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reduction of ecosystem services such as pollination, and water pollution (Kevan and Phillips 2001).

IPM is a strategic approach to managing pests that uses multiple tactics to manage all of the pest threats observed in a crop system (Barzman et al. 2015). The first step in an IPM approach requires proper identification of pest and pathogen species as well as beneficial species. Once these species are known, an IPM package can be designed (Dinakaran et al. 2013). An IPM package consists of tactics or practices that address pest problems in a crop in a given location over a whole growing season (Barzman et al. 2015; Grasswitz 2019).

Confirmation of the pest in a given field can be done using systematic observations. Some pest species can be anticipated because they have appeared in previous years. Preventative measures may be incorporated into the package based on this anticipation. These measures may include selection of resistant crop varieties, manipulation of planting dates, soil amendments, sanitizing seed treatments, encouragement of natural enemies by establishing plant species that are food sources for natural enemies and refraining from using pesticides that are harmful to natural enemies, mechanical barriers such as using a row cover on the seedbed, and so on (Grasswitz 2019). For IPM decisions, a regular monitoring regime (scouting) is established to ascertain when pest species appear during a season, how much of a threat they are to the crop, and whether natural enemies are present and offer pest suppression. Monitoring can be aided by sex pheromone traps and sticky cards, as well as human observations (Barzman et al. 2015). Within-season control practices can include rogueing of diseased plants and judicious pesticide use when necessary, based on crop monitoring. Each practice is selected based on its efficacy, economic benefits, and risks to human health and the environment (Barzman et al. 2015). A challenge for developing and implementing an IPM program is to successfully balance yield, quality, and profits while reducing pesticide use. Several IPM programs have been introduced for tomato production in Asia. Pretty and Bharucha (2015) analyzed IPM implementation programs in several countries in East Asia and Africa and found yield increases from 3.3 to 17.5 t/ha, demonstrating the critical role of IPM for the food production. In Bangladesh, where the pesticide applications were significantly reduced, profit increased by 39% (Rahman et al. 2018).

The development of appropriate management strategies is essential to increase yield and profit for Cambodian tomato farmers. Here, we explored the impacts of an IPM package on pest infestation, yield, income, cost, and profit on 12 tomato farms during both dry and wet seasons in 2019. We hypothesized that the IPM package would be at least as effective as conventional management at controlling tomato pests and that profitability would not be harmed by adopting an IPM management package. The research was done on farmers' fields using a participatory research approach (Rajotte et al. 2005).

Materials and Methods

Field trials were conducted during the dry season (October 2018 to March 2019) and wet season (May to October 2019) at 12 farms located in four districts, including Chi Kraeng, Angkor Thom, Batheay Srei, and Pouk of Siem Reap, Cambodia. Dry-season temperatures ranged from 21.5 to 36°C, with a total rainfall of 370 mm, with and 18 to 71% relative humidity. The rainy season had total rainfall of 1,050 mm, with temperatures ranging from 22.5 to 35.5°C and 33 to 100% relative humidity. We followed an on-farm research approach that underscored participatory experimental trials and surveys (Darnhofer et al. 2012; Norton et al. 1999), essentially as described by Malacrinò et al. (2020). Briefly, we compared IPM and conventional management treatments and a control. The IPM treatment protocol was standardized across farms (details below) (Dinakaran et al. 2013) whereas the conventional treatment comprised a mix of farm practices; farmers managed their conventional plots according to their usual practices.

Agronomy. Soil was plowed and fertilized with compost or manure (5 t ha^{-1}) and lime (320 kg ha^{-1}) about 2 weeks before transplanting. Next, raised beds (80 cm wide by 30 cm high) were established with 70-cm bed rows and a drip irrigation system was installed lengthwise in the middle of each bed and covered with silver plastic mulch a week before transplanting. Tomato plants (3 weeks old) were transplanted at a density of 2 plants m^{-2} and vertically grown on bamboo and wooden poles (1 m) and plastic string. Tomato plants were irrigated daily or every 2 days according to crop needs. Plots were fertilized with nitrogen (N) at 50 kg ha^{-1}, phosphorus (P) at 60 kg ha^{-1}, potassium (K) at 250 kg ha^{-1}, calcium at 18 kg ha^{-1}, and magnesium at 0.3 kg ha^{-1} during both dry and rainy seasons. Fertilization was divided between basal fertilizer and fertigation applications, with 40% of total N, 30% of total P, and just 5% of total K; the basal application was performed during the second plow and weekly fertigation applications.

Pest management. The IPM treatment targeted aphids, fruit borer, leaf miner, thrips, spider mite, whitefly, worms (*H. armigera* and *Spodoptera* spp.), bacterial wilt, damping off, Fusarium wilt, and powdery mildew (Table 1). IPM treatment comprised seedlings planted in seed trays in coco peat (Jiffy DecoGro, Jiffy International, Ås, Norway) mixed with *Trichoderma viride* (Royal University of Agriculture, Cambodia), an avirulent soil fungus used as a biofungicide to manage diseases caused by fungal pathogens, at 1 g $liter^{-1}$ of coco peat, protected by insect exclusion nets (50 mesh $in.^{-1}$). Then, seedlings were transplanted into the plot and watered in with a *T. viride* and cow manure slurry solution after 3 weeks.

Next, plants were sprayed weekly with a mix of three biopesticides: *Bacillus thuringiensis* subsp. *aizawa* (Table 1) (Ladda Co., Ltd., Thailand), *B. subtilis* (Tab Innovation Co., Ltd., Thailand), and *Beauveria bassiana* (Tab Innovation Co., Ltd.) (Supplementary Table S1) at 0.4, 0.25, and 0.4 kg ha^{-1}, respectively. In addition, we periodically sprayed sodium tetraborohydrate decahydrate in orange essential oil (Prev-Am; ORO Agri Inc.) when needed to manage insect damage (aphids, whiteflies, or thrips) at 0.4% per 100 gal. Furthermore, conventional pesticides were used in the trial, including imidacloprid (Confidor 200SL; Bayer, Germany), which was sprayed once by each farmer at a rate of 667 ml ha^{-1} during the dry season to control thrips, and metalaxyl (Kalaxy 35WP; Papaya Trade Co., Cambodia) for late blight sprayed one or two times as needed at a rate of 590 g ha^{-1}, once

TABLE 1
Arthropod pests and pathogens scored in tomato plants found during both the dry and rainy seasons

Pest category, common name	Scientific name
Arthropods	
Aphid	*Macrosiphum euphorbiae*
Fruit borer	*Leucinodes orbonalis* Guenee
Leaf miner	*Liriomyza sativae*
Thrip	*Frankliniella schultzei*
Spider mite	*Tetranychus urticae*
White fly	*Bemisia tabaci* (Genadius)
Worms	*Helicoverpa* sp., *Spodoptera* sp.
Pathogens	
Bacterial wilt	*Ralstonia* sp.
Damping off	*Phytophthora* sp.
Fusarium wilt	*Fusarium* sp.
Powdery mildew	*Oidium* sp.

or twice a week during the rainy season (Supplementary Table S1). We used pheromone lures and yellow sticky traps (35 by 40 cm) for monitoring insect populations. Disease incidence and severity were monitored from plant symptoms in the field (10 plants/plot). The conventional treatment is summarized in Supplementary Table S2. Seedlings were grown in seed trays using field soil; in total, 15 different pesticides were sprayed (11 insecticides and 4 fungicides) during both dry and rainy seasons. Tomato plants of control plots were grown in coco peat trays without insecticide or fungicide applications.

IPM package components were selected using our experience in similar systems in other countries such as Bangladesh, Nepal, and India. The work in Cambodia is considered adaptive research; thus, the successful packages developed in other countries would be validated in Cambodia (Dinakaran et al. 2013; Malacrinò et al. 2020; Rajotte et al. 2005).

Data collection and analysis. We scouted all plots weekly and selected five random plants per treatment and measured damage by arthropod pests and pathogens (Table 1). We followed a protocol essentially as described by Malacrinò et al. (2020), in which pest and disease levels on each plant were scored on a scale from 0 to 3, which was granularly calibrated for replicability between farms. Damage or severity was classified as follows: 0 = none, 1 = little, 2 = moderate, and 3 = severe (Supplementary Table S3). We also measured yield, input costs (excluding labor), income from sales, and profit. Input costs included expenses from fertilizers to trellis system; values were adjusted for depreciation. Farmers documented yield, including marketable weight (kilograms) and price of tomato fruit per kilogram (U.S. dollars [USD]) for each treatment. Then, we calculated costs and benefits for each treatment by subtracting total expenses from income produced by marketable tomato.

For statistical analyses, we used a generalized linear mixed-effects model (GLMM) with treatments (IPM, conventional, and control) as a fixed effect and pest, farm, and sampling week as random variables. Analyses of damage scores for each species pest were similarly analyzed, without species pest as a random variable. Models were fitted with a Poisson family error distribution because data were counts and log link function using the *glmer* function from the *lme4* package of R (Bates et al. 2015). Then, we assessed a treatment's effect using type II Wald χ^2 from the package *car* and *Anova* function. Posthoc analyses such as pairwise contrasts using Tukey's multiple comparisons were conducted using the package *emmeans*. Pests for which at least one treatment did not have an average damage score of at least 0.02 (i.e., at least 1 of 50 plants was scored as 1 or higher per week) were not statistically analyzed due to lack of data and model convergence issues.

We used a linear mixed-effects model to analyze yields, costs, incomes, and profits data using the *lmer* function, with treatment as a fixed effect and farm as a random variable; then, pairwise contrasts were inferred using Tukey's multiple comparisons, as described above. Because growing conditions were different between dry and rainy seasons, statistical analyses were separately performed for each season using R 4.0.2 (R Core Team 2013).

Results

Damage. The global analysis (GLMM) showed no significant differences in disease incidence among the three treatments. However, during the dry season, Fusarium wilt and damping-off was decreased by 45 and 55%, respectively, in IPM plots compared with conventional management and control plots (Fig. 1; Table 2). In contrast, bacterial wilt and powdery mildew were not significantly affected by management practices. In 2019 (wet season), disease incidence followed a similar trend as in 2018 (Table 2).

GLMM showed no significant differences in arthropod pests among the three types of plots. However, the incidence of worms (*Helicoverpa* or *Spodoptera* spp.) was reduced by 25% (Fig. 1; Table 3). During the wet season, the arthropod pest populations decreased in all experimental plots; however, the lowest pest incidences were observed in plots where the IPM practices were implemented (Table 3).

Productivity. During the dry season, tomato yield increased 6% in plots that used IPM practices compared with plots using conventional or no treatment. Income increased 9 and 14%in IPM plots relative to conventional and control plots, respectively. The costs associated with using the IPM package in the dry season were 5% higher than in plots using conventional management and 29% higher than control plots (Table 4). During the rainy season, tomato yield in IPM plots was 8% higher than in plots using conventional management and 32% higher than the untreated control. On average, the income during the rainy season in IPM plots increased by 63%, and the costs were only 4% higher than plots using conventional management and 11% higher than the control. The cost associated with the IPM package was 3.5% higher than in plots using conventional management and 26% higher than in control plots (Table 4). The profit in IPM plots was 15% higher than in conventional management and 40% higher than in control plots (Table 4).

Discussion

IPM practices have long been recognized as essential for sustainable tomato production (Pretty and Bharucha 2015; Strand 1998). Few studies, however, have examined the effects of IPM on tomato production in Cambodia (Mund 2011), and fewer still have evaluated the differences between IPM and conventional practices. The results of our field experiment demonstrate that using an IPM package reduces the arthropod pests and disease incidence in tomato crops during both dry and wet seasons in Cambodia.

Plots in which the IPM package was deployed had significantly higher yield and income than plots using conventional management. The IPM package used cultural, physical, biological, and chemical control tools, including several that increased the cost on average by 30% compared with conventional management. However, the successful control of tomato pests resulted in an average

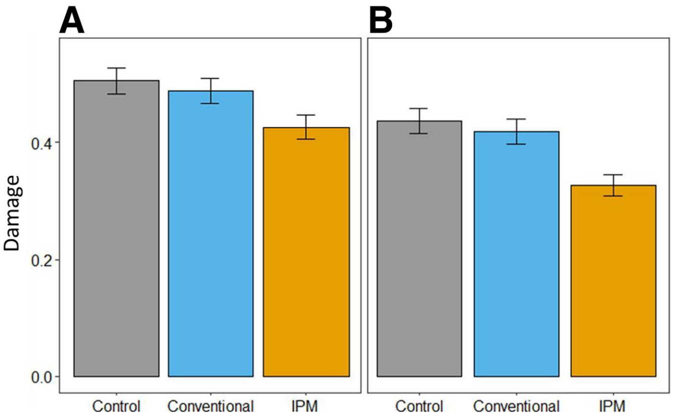

FIGURE 1

Damage scores for tomato under conventional management, integrated pest management (IPM), or control (no management) during **A,** rainy and **B,** dry seasons in Cambodia. Bars represent mean ± standard error.

TABLE 2

Disease severity in tomato plants during both dry and rainy seasons in small-farm scales[z]

Plant pathogen	χ^2	*P*	Control	Conventional	IPM
Dry season					
Bacterial wilt	4.19	0.1225	0.12 ± 0.05	0.12 ± 0.05	0.05 ± 0.03
Fusarium wilt	11.09	0.003	0.55 ± 0.10	0.49 ± 0.10	0.27 ± 0.07
Powdery mildew	0.01	0.9944	0.5 ± 0.04	0.49 ± 0.04	0.5 ± 0.04
Damping-off	6.83	0.028	0.27 ± 0.07	0.25 ± 0.07	0.12 ± 0.05
Unknown disease	0.13	0.9351	1.00 ± 0.11	1.05 ± 0.10	1.00 ± 0.11
Rainy season					
Bacterial wilt	0.99	0.6086	0.15 ± 0.05	0.17 ± 0.05	0.12 ± 0.04
Fusarium wilt	17.59	0.0001	0.55 ± 0.10	0.49 ± 0.10	0.15 ± 0.07
Powdery mildew	0.06	0.9692	0.50 ± 0.04	0.49 ± 0.04	0.50 ± 0.04
Damping-off	13.5	0.0011	0.27 ± 0.07	0.25 ± 0.07	0.12 ± 0.05
Unknown disease	0	1.00	0.30 ± 0.11	0.30 ± 0.10	0.30 ± 0.11

[z] IPM = integrated pest management. Dry season: $\chi^2 = 8.81$; $P = 0.01216$ and rainy season: $\chi^2 = 19.25$, $P < 0.0001$ (mean ± standard error).

TABLE 3

Arthropod pest populations in tomato plants during both dry and rainy seasons in small-farm scales[z]

Arthropod pest	χ^2	*P*	Control	Conventional	IPM
Dry season					
Aphids	2.31	0.3138	0.11 ± 0.02	0.08 ± 0.02	0.05 ± 0.02
Fruit borer	0.01	0.9933	0.42 ± 0.04	0.41 ± 0.04	0.41 ± 0.04
Leaf miner	0.19	0.9057	0.62 ± 0.04	0.58 ± 0.04	0.59 ± 0.04
Whitefly	0.24	0.8825	0.9 ± 0.02	0.85 ± 0.03	0.93 ± 0.03
Worm	2.43	0.2954	0.48 ± 0.048	0.52 ± 0.04	0.39 ± 0.04
Rainy season					
Aphids	NA	NA	NA	NA	NA
Fruit borer	0.8	0.6676	0.42 ± 0.04	0.41 ± 0.04	0.41 ± 0.04
Leaf miner	1.08	0.581	0.62 ± 0.04	0.58 ± 0.04	0.59 ± 0.04
Whitefly	1.33	0.5133	0.98 ± 0.02	0.87 ± 0.03	0.84 ± 0.03
Worm	6.98	0.0304	0.48 ± 0.04	0.52 ± 0.04	0.20 ± 0.04

[z] IPM = integrated pest management. Dry season: $\chi^2 = 10.23$; $P = 0.01216$ and rainy season: $\chi^2 = 19.25$, $P < 0.0001$ (mean ± standard error). NA = not available.

TABLE 4

Analysis of yield, income, costs, and profit from tomato dry season and rainy season[y]

Season, treatment[z]	Yield (kg m^{-2})	Income (USD m^{-2})	Costs (USD m^{-2})	Profit (USD m^{-2})
Dry				
Control	2.67 ± 0.11 a	0.79 ± 0.04 a	0.51 ± 0.007 a	0.21 ± 0.04 a
Conventional	2.91 ± 0.13 a	0.79 ± 0.04 a	0.68 ± 0.007 b	0.14 ± 0.04 a
IPM	3.10 ± 0.11 b	0.84 ± 0.04 b	0.72 ± 0.007 c	0.12 ± 0.04 b
F	7.78	7.39	264.86	3.69
DF	22	22	22	22
P	0.0027	0.0034	<0.0001	0.04
Rainy				
Control	1.69 ± 0.12 a	1.05 ± 0.08 a	0.51 ± 0.003 a	0.52 ± 0.08 a
Conventional	2.28 ± 0.12 b	1.41 ± 0.08 b	0.63 ± 0.003 b	0.78 ± 0.08 b
IPM	2.49 ± 0.12 b	1.54 ± 0.08 b	0.66 ± 0.003 b	0.88 ± 0.08 b
F	40.38	41.43	801.10	20.18
DF	22	22	22	22
P	<0.0001	<0.0001	<0.0001	<0.0001

[y] Different letters indicate significant pairwise differences between values within the same column at the $P < 0.05$ level.

[z] IPM = integrated pest management. Dry season: $\chi^2 = 3.69$; $P = 0.0412$ and rainy season: $\chi^2 = 26.11$, $P < 0.0001$ (mean ± standard error).

of 45% more profit in plots using the IPM approach in both seasons than in those using conventional management.

The costs of IPM practices were higher than conventional management and no-spray trials. However, adopting this IPM program led to substantial profit increases during the rainy season and a similar profit compared with the no management program. The IPM strategy used on these small farms was demonstrated to be a success when multiple tactics such as physical control and biological and synthetic pesticides were used. Thus, sustainable tomato production on small farms in Cambodia could benefit from adopting IPM packages that align with tomato plant development and the biology and ecology of pests and diseases.

Incidence of the soilborne disease Fusarium wilt and damping-off was significantly reduced during both dry and wet seasons in tomato in the IPM program treated with *T. viride* as seedling transplants and subsequently with *Bacillus subtilis* and *Pseudomonas fluorescens* applications. These microbes have been shown to be successful biocontrol agents of pathogens such as root rot fungi (Elad 2000). Biocontrol agents degrade the cell walls of the plant pathogen (de la Cruz et al. 1995). Bacterial wilt, Fusarium wilt, powdery mildew, damping off, and virus symptoms were all detected but at low infection levels in IPM plots. This suggests the efficacy of the rational use of biopesticides within an IPM program (Dara 2016).

The numerical differences in arthropod pest incidence in IPM plots resulted from the combined effect of physical, biological, and synthetic control practices. Physical control such as the use of insect exclusion nets during the seedling stage has been shown to reduce early insect infestation, resulting in a significant reduction in tomato damage (Caroline et al. 2017; Singh et al. 2018). Spraying *B. thuringiensis* and *Beauveria bassiana* significantly reduced damage caused by insects during both dry and rainy seasons, suggesting a synergistic impact on a wide range of tomato pests. Several studies have shown that *Bacillus thuringiensis* bacterium controls many insect pests, including *H. zea*, *Manduca sexta,* and *Spodoptera frugiperda* (Arthurs and Dara 2019). In addition, studies have shown that *B. thuringiensis* reduces leafminer populations (Badran et al. 2016; Jamshidnia et al. 2018) and sucking insects such as whiteflies and aphids (Badran et al. 2016). Aphid populations were absent during the rainy season, possibly due to the environmental constraints and colonies of *B. bassiana* on the farms. The effects of the fungus *B. bassiana* on the control of insect pest populations have been well documented (Wari et al. 2020). Other biological control agents such as *B. thuringiensis* directly impact caterpillars attacking foliage and fruit (i.e., *S. frugiperda* and *M. sexta*). Alternating biopesticides and synthetic insecticides seem to be a good alternative to reduce arthropod pest impact as well as insecticide use in tomato crops of Chi Kraeng, Angkor Thom, Batheay Srei and Pouk, Siem Reap provinces.

Small-scale farms are a fundamental component of agricultural production in Cambodia. They have an important role in promoting social benefits of sustainable agriculture, including the conservation of natural resources and biodiversity, as well as the enhancement of local food security (Grasswitz 2019). Low tomato production in Cambodia may result from the combined effect of poor soil fertility, unfavorable weather, poor-quality seeds, and high cost of inputs or poor postharvest knowledge of the growers (Bhattarai et al. 2011). Growing tomato crops can provide high returns to small-scale farmers, thus reducing the importation from neighboring countries such as Vietnam and Thailand (Bhattarai et al. 2011).

Challenges associated with the cost effectiveness of IPM may be addressed by prioritizing phytosanitary problems per location; thus, different IPM packages may be designed in response to a broader range of farmers' needs. An IPM approach may reduce the risk associated with the development of resistance in tomato pests. The success of tomato production in Cambodia relies on a better understanding of the pest population dynamics combined with cultural, physical, and rational applications of biopesticides and synthetic pesticides.

In summary, our results indicate that our IPM package approach can significantly reduce tomato pest severity and disease incidence and that rational use and timing of biopesticide applications can result in sustainable insect and disease control over time. Moreover, this study demonstrates the cost effectiveness of implementing IPM tactics on small farms.

Data availability. The data that support the findings of this study are available on request from the corresponding authors M. F. Porras and M. E. O'Rourke.

Acknowledgments

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