Chemosphere 240 (2020) 124926

Contents lists available at ScienceDirect

Chemosphere

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

Environmental impacts of reduced-risk and conventional pesticide programs differ in commercial apple orchards, but similarly influence pollinator community

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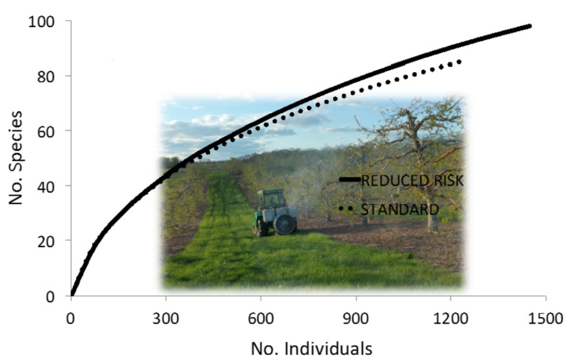
HIGHLIGHTS

- Community-level ecotoxicological impacts of reduced-risk and conventional pest management programs in apple orchards were assessed.
- Pesticide inputs and response of bees and syrphid flies were quantified.
- Community response of bees and syrphid flies did not differ between pesticide programs.
- Reduced-risk pesticide program reduced the use of organophosphates and pyrethroids.
- Environmental impact of pesticide inputs was greatly reduced in reduced-risk program.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 26 July 2017
Received in revised form
12 September 2019
Accepted 20 September 2019
Available online 21 September 2019

Handling Editor: Jim Lazorchak

Keywords:
Pollinators
Community ecotoxicology
Reduced-risk pesticides
Organophosphates
Neonicotinoids

ABSTRACT

Insect pollinators such as bees and syrphid flies play a crucial role in pollinating many food crops, and their diversity and abundance may be influenced by pesticide application patterns. Over three years, we assessed the ecotoxicological impacts on the diversity and abundance of bees and syrphid flies between reduced-risk pesticide programs and standard, conventional pesticide programs in paired plots at six spatially distinct commercial apple orchards. In particular, we quantified pesticide inputs, environmental impact, and community response of bees and syrphids to these pesticide programs. Relative environmental impacts of reduced-risk versus conventional pesticide programs were calculated using Environmental Impact Quotient analysis, while ecological impacts were characterized by assessing the abundance, richness, and species assemblages of bees and syrphids. Adopting a reduced-risk pesticide program for apple pest management reduced the use (in terms of kg a.i./ha) of organophosphate and pyrethroid insecticides by approximately 97.6% and 100% respectively, but increased the use of neonicotinoid pesticides (acetamiprid, imidacloprid, thiacloprid) by 40.4% compared to the orchards under standard conventional pesticide program. Regardless of pesticide inputs, abundance, richness and species assemblages of bees and syrphids did not differ between reduced-risk and conventional pest management programs. However, the environmental impact of pesticide inputs was reduced by 89.8% in

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https://doi.org/10.1016/j.chemosphere.2019.124926
0045-6535/

reduced-risk pesticide program. These findings suggest that the implementation of reduced-risk pesticide program may reduce pesticide environmental impact, in addition to being safer to farm workers, without adversely affecting the robust community composition of bees and syrphids in commercial apple orchards in the mid-Atlantic region.

1. Introduction

Effective integrated pest management (IPM) of the arthropod pest complex infesting apples in the northeastern United States is challenging (Howitt, 1993; Hogmire, 1995; Agnello et al., 2009; Hull et al., 2009). Ideally, these IPM programs should support beneficial arthropods, including many species of predators and parasitoids that biologically control several key pests, as well as wild pollinators such as bees and syrphid flies in the orchard ecosystem. Apple growers use different pest management tactics, including various conventional and reduced-risk insecticides, sex pheromone-based mating disruption and microbial pesticide products (Agnello et al., 2009; Hull et al., 2009; Joshi et al., 2008). Maintaining pest densities below economic thresholds, while minimizing non-target effects of pesticides on predators, parasitoids and pollinators, is key to sustainable apple production.

Pesticide use patterns may change over time as new products become available and others leave the market. Recently, the use of older insecticides such as the organophosphates (OP) and carbamates, which were the main components of apple insecticide programs for 40 years, has declined mainly due to regulatory actions such as the Food Quality Protection Act (FQPA) of 1996 (Jones et al., 2010; Sjöberg et al., 2015). The FQPA focuses on reducing human health and environmental risks, which favors the registration "soft" pesticides with low mammalian toxicity termed "reduced-risk" pesticides (US-EPA, 1997). Reduced-risk pesticides have one or more of the following advantages over the older, more broadly neurotoxic compounds: (a) lower risk to human health (very low toxicity to mammals), b) lower toxicity to other non-target organisms, c) lower potential for contamination of groundwater, surface water or other valued environmental resources, d) lower use rates, low pest resistance potential, and e) lesser impact on natural enemies of pests, thus broadening the adoption and effectiveness of IPM strategies. New IPM programs for apple and peach were developed in the eastern US that incorporated reduced-risk pesticides (Agnello et al., 2009). Field studies have shown that IPM programs based on reduced-risk insecticides resulted in lower active ingredient rates and the protection of biological control agents (Agnello et al., 2009; Atanassov et al., 2002, 2003; Biddinger et al., 2014), however the impact on the apple pollinator community (bees and syrphids) has yet to be documented.

Insect pollinators are required for pollination of several specialty crops comprising some widely consumed fruits, nuts and vegetables (Calderone, 2012; Delaplane and Mayer, 2000; Losey and Vaughan, 2006). However, significant declines in pollinator populations have been reported across the globe (Cameron et al., 2011; Dupont et al., 2011; Genersch et al., 2010; Hayes et al., 2008; Lee et al., 2015; Meixner, 2010; Pirk et al., 2014; van der Zee et al., 2012), raising food security concerns (Garibaldi et al., 2011; Potts et al., 2010). Among the several interacting stressors (such as diseases, pests, unavailability of floral resources, lack of habitat, and insecticides) thought to be linked to the population declines (Spivak et al., 2011; Smith et al., 2013), many recent reports suggest agricultural pesticides may play an important role (Chakrabarti et al., 2015; Ciarlo et al., 2012; Di Prisco et al., 2013; Fine et al., 2017; Henry et al., 2012; Hodgson et al., 2011; Johnson et al., 2013; Krupke et al., 2012; Mullin et al., 2015; Pettis et al., 2013; Rundlöf et al., 2015; Whitehorn et al., 2012). However, pesticides are a necessary input to commercial crop production, so there is need for an IPM approach that not only economically manages pests, but also protects pollinator health as described in the emerging Integrated Pest and Pollinator Management (IPPM) approach (Biddinger and Rajotte, 2015).

Apple is a pollinator-dependent major fruit crop, and flower-visiting arthropods such as bees and syrphids are indispensable in pollinating commercial orchards throughout the US (Free, 1964; Tepedino et al., 2007). In the eastern US, where a majority of apple orchards are surrounded by a heterogeneous landscape (Kammerer et al., 2016a), most apple growers rely upon wild bees and syrphids for pollination (Biddinger et al., 2013, Biddinger and Rajotte, 2015; Gardner and Ascher, 2006; Joshi et al., 2011; Park et al., 2010). Many pesticides used in these apple orchards are known to be harmful to pollinators (Biddinger et al., 2013; Hopwood et al., 2012), with the likely primary route of exposure occurring during the short 10–12 days apple bloom in the early spring. However, beneficial arthropods, including pollinators, may also be exposed to pesticides in the ground cover or adjacent habitat throughout the six-month growing season of commercial orchards (Biddinger et al., 2014; Park et al., 2015).

Conducting farm-level ecological assessments can gauge the impacts of pesticides on beneficial arthropods such as pollinators. In this study, we compared the ecotoxicological impacts of reduced-risk versus conventional pesticide programs on the community composition of bees and syrphids in commercial apple orchards for the full apple growing season over a three-year period. Additionally, we compared broader environmental impacts by calculating the Environmental Impact Quotient (EIQ), which is a standard measure of pesticide impact on the environment and farm worker safety (Agnello et al., 2009).

2. Materials and methods

2.1. Study orchards

This study was conducted on commercial apple farms in Pennsylvania during 2007–2009. In 2002, we selected six orchards (five in Adams County and one in Center County), and within each designated paired blocks (i.e., side-by-side plots) (~3–4 ha each) for comparison of the standard conventional pesticide program and reduced-risk program. Each block had already experienced four crop seasons in its respective pesticide program before this study began to allow the arthropod communities to stabilize before the orchards were assessed. Each pair of blocks had similar cultivars, rootstocks, tree sizes and ages.

2.2. Pest management programs

General information on the type and timing of insecticide applications relative to pest and apple phenology in this region, is summarized in Agnello et al. 2009; see Table 1, Figs. 2 and 4).

Table 1
Summary of pest management inputs and environmental impact quotients (EIQ) for standard conventional (STND) and reduced risk (RR) pesticide programs in commercial apple orchards in Pennsylvania during 2007–2009.

Input	Standard (STND)	Reduced Risk (RR)	Difference in kg a.i./ha (RR compared to STND)	% Change (RR compared to STND)
Organophosphate (kg a.i./ha)	3.82(0.710)	0.0934 (0.093)	−3.730	−97.6
Pyrethroid (kg a.i./ha)	0.003 (0.002)	0.000 (0.000)	−0.003	−100.0
Antibiotic (spinosad, ememectin benzoate, spinetoram) (kg a.i./ha)	0.065 (0.019)	0.102 (0.021)	0.037	56.6
Tetramic Acid (spirotetramat) (kg a.i./ha)	0.000 (0.000)	0.009 (0.009)	0.009	RR only
Anthranilic Diamide (chlorantraniliprole, flubendiamide) (kg a.i./ha)	0.053 (0.017)	0.112 (0.030)	0.059	111.1
Miticide (incl. abamectin) (kg a.i./ha)	0.021 (0.016)	0.000 (0.000)	−0.021	−100.0
Insect growth regulators (buprofezin, methoxyfenozide, novaluron, pyriproxyfen) (kg a.i./ha)	0.132 (0.047)	0.141 (0.040)	0.009	6.6
Oxadiazine (indoxacarb) (kg a.i./ha)	0.012 (0.008)	0.055 (0.019)	0.043	363.9
Nicotinoids (kg a.i./ha)	0.212 (0.038)	0.298 (0.035)	0.086	40.4
Total (kg a.i./ha)	4.36 (0.660)	0.811 (0.118)	−3.547	−81.4
Pheromone Ties (number per hectare)	82.37 (37.37)	253.97 (50.413)	171.601	208.3
Cumulative EIQ Field Rating	185.62 (29.07)	18.84 (2.870)	−166.772	−89.8

Note: Values in parentheses represent ±SE.

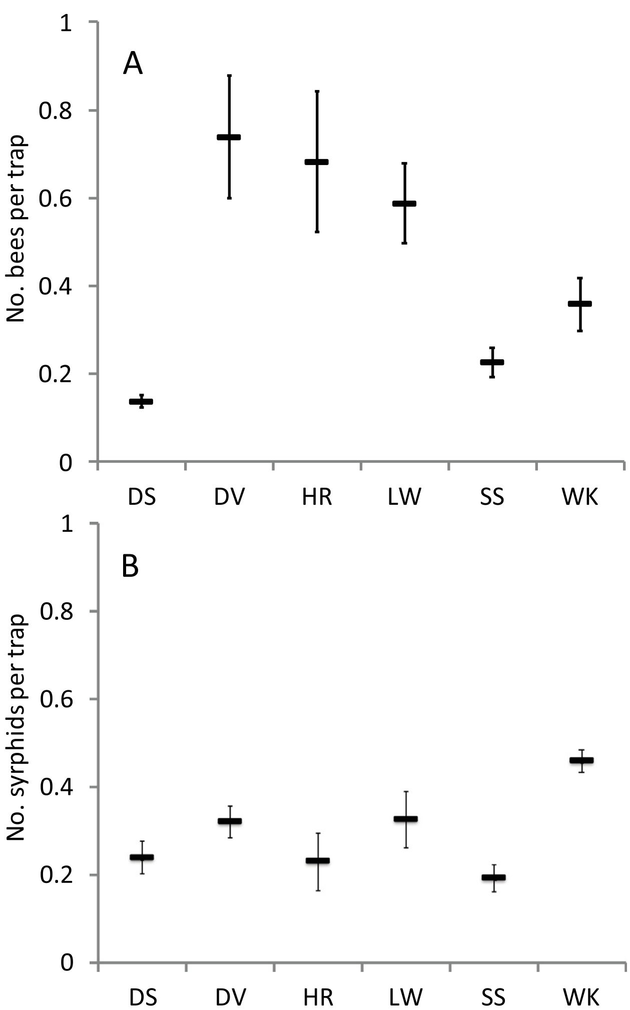

Fig. 1. Mean (±SE) number of bees (A) and syrphids (B) caught per trap among the six research site locations (abbreviations based on names of the commercial farms).

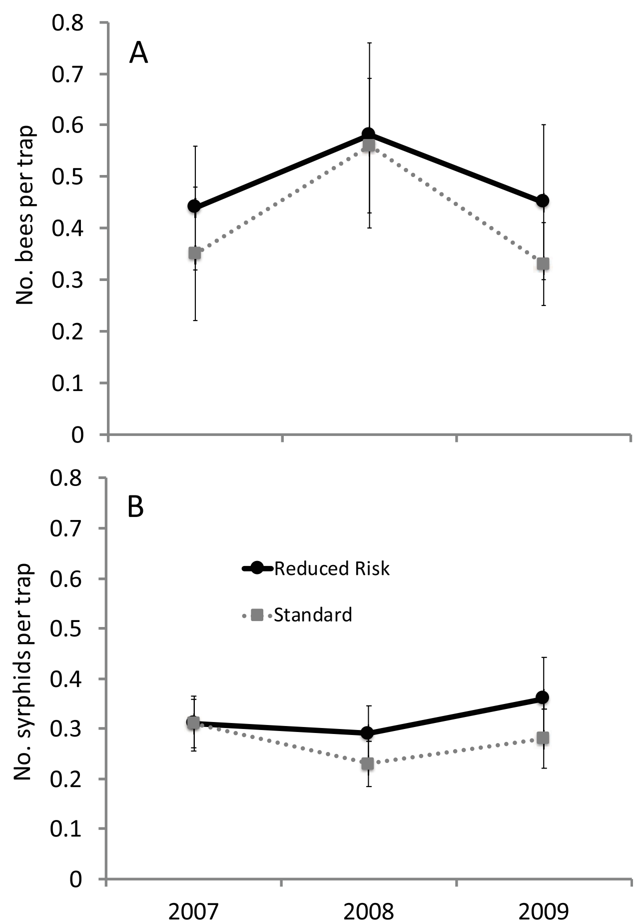

Fig. 2. Mean (±SE) number of bees (A) and syrphids (B) caught per trap in reduced risk and standard pest management programs over three years.

Commonly targeted pests in the apple orchards included: San Jose scale [(*Quadraspidiotus perniciosus* (Comstock)], rosy apple aphid [*Dysaphis plantaginea* (Passerini)], tarnished plant bug [*Lygus lineolaris* (Palisot de Beauvois)], oblique-banded leafroller [*Choristoneura rosaceana* (Harris)], Oriental fruit moth [*Grapholita molesta* (Busck)], plum curculio [*Conotrachelus nenuphar* (Herbst)], codling moth [*Cydia pomonella* (Linnaeus)], tufted apple bud moth [*Platynota idaeusalis* (Walker)] and apple maggot (*Rhagoletis pomonella* Walsh). In general, apple orchard blocks under the standard conventional insecticide program received applications of a range of conventional pesticides (standard pesticides of growers'

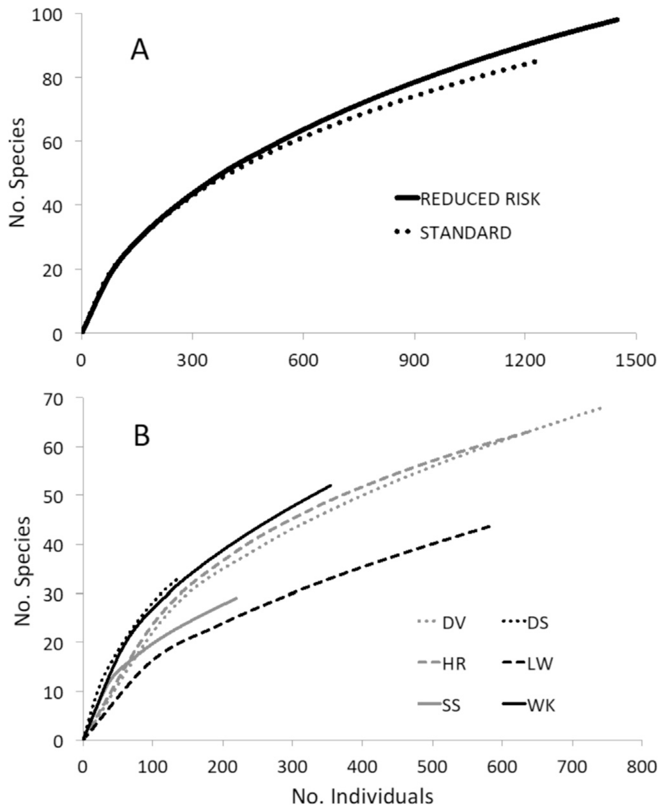

Fig. 3. Individual-based rarefaction curves depicting species accumulation of bees in apple orchards from 2007 to 2009. Species accumulation is compared (A) between reduced-risk and conventional standard pesticide programs, and (B) among the six research sites (abbreviations based on the names of the commercial farms).

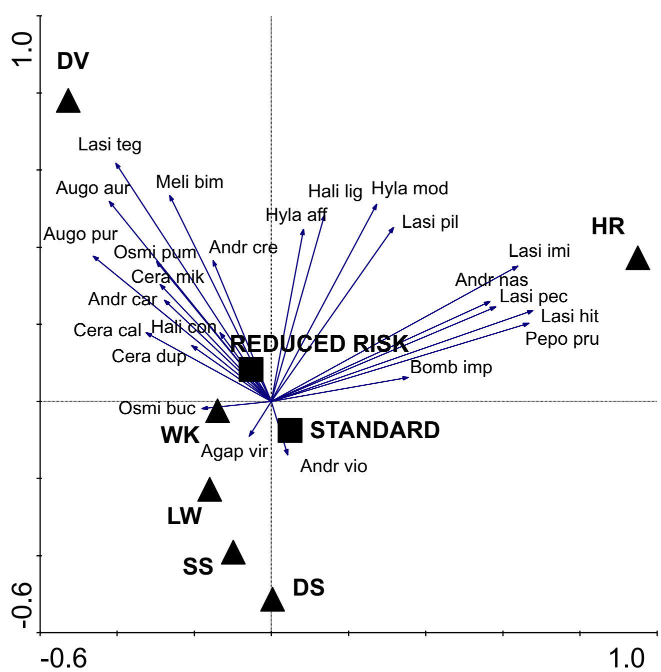

Fig. 4. RDA biplot depicting associations among bees (vectors), pest management programs (squares), and orchard sites (triangles; abbreviations based on names of the commercial farms). Species names are abbreviated; full names can be found in Table 2.

choice at that time) targeting vulnerable pest developmental stages throughout the crop season. Typically, conventional growers heavily relied on organophosphate (azinphosmethyl, chlorpyrifos, diazinon and phosmet), carbamate (carbaryl, used for only fruit thinning after fruit set), and pyrethroid (lambda cyhalothrin) insecticides, insect growth regulators (methoxyfenozide, pyriproxyfen), miticides (spiridiclofen, abamectin), and some other common management practices (such as use of mating disruption products) available at that time. Pesticide selection and application timing in these orchards were determined by either growers or private consultants.

In orchards under reduced-risk management programs, various reduced-risk insecticides as well as mating disruption sex-pheromone chemicals were applied based on the recommendations of a crop consultant. In these orchards, D. Biddinger (Penn State Fruit Research Center) served as a crop consultant and made all decisions about selecting products and application timing. In general, we used the following reduced-risk products [target pests for each product are described in Table 1 of Agnello et al. (2009)]: (a) insect growth regulators (buprofezin, methoxyfenozide, novaluron, pyriproxyfen); (b) anthranilic diamides (chlorantraniliprole, flubendiamide); (c) tetramic acid (spirotetramat); (d) antibiotic/microbials (spinosad, ememectin benzoate, spinetoram); (e) oxadiazines (indoxacarb); (f) neonicotinoids (acetamiprid, imidacloprid, thiacloprid); and (e) pheromones (Isomate-C TT®, Isomate Rosso®, and Isomate CM/OFM TT®).

2.3. Sampling of bees and syrphids in study orchards

We sampled bees and syrphids using pan traps (yellow, dark blue, and white colored plastic bowls) (Solo®, Solo Cup Company, Lake Forest, Illinois, USA). Sampling occurred on a weekly basis from spring (bloom time) through fall (till the end of crop season) over three years (Y1: 22 weeks; Y2: 29 weeks; Y3: 30 weeks). For each sampling event, two sets of three pan trap clusters (blue, yellow and white) were deployed (between 800hr and 1200hr EDT) within each block and collected after 24 h. These traps were deployed in study orchards based on the local weather forecast to avoid inclement weather and heavy rainfall. Pan traps contained tap water with a few drops of liquid detergent (Blue Colored Dawn® Dish Soap; Procter and Gamble, Cincinnati, Ohio, USA) to reduce surface tension and prevent insects from escaping. Trap clusters were placed on the ground in the herbicide strip between trees in a row so they were not obscured by vegetation and in the center of each orchard block to minimize field edge effect on sampling.

2.4. Sample processing

All insect samples were sorted, pinned and identified to species. Bees were identified to species level using dichotomous keys (Mitchell, 1960, 1962; Michener et al., 1994; Michener, 2000) and the online taxonomic resource, Discover Life (www.discoverlife.org). Identifications were done by L. Donovall (PA Department of Agriculture), D. Biddinger (Penn State University), J. Gibbs (*Lasioglossum* - Michigan State University), K. Wright (*Melissodes* - University of New Mexico), R. Jean (*Andrena* — Saint Mary-of-the Woods College), and S. Droege (United States Geologic Survey). Syrphid flies were identified to species level using reference specimens identified by D. Biddinger, C. Thompson (Smithsonian Collection), and published keys (Miranda et al., 2013; Vockeroth, 1992) as well as available online taxonomic resources, such as Bug Guide (bugguide.net), Canadian National Collection of Insects, Arachnids, and Nematodes (www.canacoll.org), and Discover Life (www.discoverlife.org).

2.5. Environmental Impact Quotient and pesticide field rating analysis

Both types of pesticide programs were compared for their impacts on the environment using Environmental Impact Quotient (EIQ) analysis to calculate cumulative EIQ values and field ratings. The EIQ value for individual pesticides is based on measures related to toxicity and persistence and the expected effects averaged across three groups: farm workers, consumers, and non-target species/environment (see Kovach et al., 1992 for full equation). EIQ values are then converted to field ratings based on application rates and % active ingredient (see: Kovach et al., 1992; Agnello et al., 2009; Biddinger et al., 2014). Pesticide records of each orchard block were used in calculating cumulative EIQ values and EIQ field ratings.

2.6. Statistical analysis

2.6.1. Pesticide use and Environmental Impact Quotient (EIQ)

For each year and all orchard blocks (under both types of pest management programs), pesticide use in terms of total kg a.i./ha, and EIQ values of pesticide inputs, as well as cumulative EIQ values of pesticides used were analyzed using an analysis of variance (ANOVA) (R Core Team, 2013).

2.6.2. Bee and syrphid abundance and richness

The effects of pest management programs and locations (i.e. orchards) on the abundance and richness of bees and syrphids were tested. Abundance values were averaged across all weeks and traps within each combination of year, location and treatment. We analyzed the main effects of pest management program and location, as well as their interaction, using a two-way analysis of variance (ANOVA) (JMP v.7, SAS Institute Inc., 2007). Abundance values of bees were log-transformed to meet the assumptions of normality.

Species richness of bees and syrphids were compared between treatments and among locations by developing rarefaction curves in EstimateS v7.5 (Colwell, 2005). Rarefaction curves depict the statistical expectation of species accumulation through iterative resampling from the data matrix. Individual-based rarefaction curves (based on 499 permutations) were used for all comparisons of species accumulation so that the length of each rarefaction curve also depicted the abundance of bees or syrphids for that specific treatment or location.

In addition to abundance and richness, we also used a multivariate statistical approach to examine associations between individual species and experimental factors. A redundancy analysis (RDA), a type of constrained ordination, in Canoco v.4.5 (terBraak and Šmilauer, 2002) examined how pest management program and orchard location influenced bee and syrphid community assemblages. For ordination, species data were centered and standardized and the significance of experimental factors was assessed through Monte Carlo permutations (n = 499) and stepwise forward selection (Lepš; Šmilauer, 2003), Biplots were developed in CanoDraw (terBraak and Šmilauer, 2002) to visualize associations between species with largest contribution to overall variance and the experimental factors.

3. Results

3.1. Comparison of pesticide use in conventional and reduced-risk programs

During all three years, the average amount of pesticide active ingredient (kg a.i./ha) used in apple orchards under reduced-risk insecticide program was 81.4% lower than the conventional insecticide programs (Table 1). Across all years, pesticide active ingredient (kg a.i./ha) use was significantly lower in orchards under reduced risk program (2007, $F_{1,10} = 12.33$, $P < 0.01$; 2008, $F_{1,10} = 11.73$, $P < 0.01$; and 2009, $F_{1,10} = 5.21$, $P < 0.05$).

In the reduced-risk insecticide program, the use of organophosphates was reduced by 97.6% (Table 1), and the use of pyrethroid insecticides was reduced by 100% (Table 1). A nominal decline was also noted in miticide use (including abamectin) in the reduced-risk program (Table 1). In contrast, use of neonicotinoid pesticides (e.g., acetamiprid, imidacloprid, thiacloprid) in reduced risk blocks increased by 40.4% compared to standard conventional pesticide program. A summary of pesticide use under both types of pesticide programs is given in Table 1.

3.2. Environmental impact quotient ratings of pesticides

Environmental impact of pesticide inputs (in terms of cumulative EIQ values) was reduced by 89.8% in reduced-risk pesticide program (Table 1). Compared to the standard conventional pesticide program, EIQ values were significantly lower in reduced risk pesticide programs in all years (2007, $F_{1,10} = 19.3$, $P < 0.005$; 2008, $F_{1,10} = 11.01$, $P < 0.01$; and 2009, $F_{1,10} = 7.07$, $P < 0.05$).

3.3. Diversity and abundance of bees

We collected 2678 bees (reduced-risk = 1449; standard = 1229) comprising 120 species (reduced-risk = 98; standard = 85) (Table 2). Bee abundance did not vary significantly over the three years of the study ($F = 0.9272_{2,\ 33}$ $P = 0.41$). Bee abundance was significantly different among orchard sites ($F = 8.48_{5,\ 24}$, $P < 0.0001$) (Fig. 1A), but not between reduced-risk and standard pest management programs ($F = 0.25_{1,\ 24}$, $P = 0.62$) (Fig. 2A). There was no significant interaction effect of site and program on bee abundance ($F = 1.21_{5,\ 24}$, $P = 0.33$). Rarefaction curves showed no difference (based on overlapping confidence intervals) in species richness between pest management programs (Fig. 3A), however rates of species accumulation were widely divergent among orchard sites (Fig. 3B).

In accordance with the bee abundance and richness results, species arrays were also found to vary significantly among orchard locations, but not between pest management programs (Fig. 4). Distinct species groupings were found for different orchard sites, with HR ($F = 5.68$, $P = 0.002$) and DV ($F = 4.99$, $P = 0.002$) accounting for most of the variation in the community assemblages (axis 1 and 2, respectively). Pest management program did not influence species assemblage patterns ($F = 1.09$, $P = 0.36$).

3.4. Diversity and abundance of syrphids

We collected 1734 syrphid flies (reduced-risk = 939; standard = 795) comprising 25 species (reduced-risk = 19; standard = 19) (Table 2). There were no significant differences in syrphid abundance over the three years of the study ($F = 0.50_{2,33}$, $P = 0.613$). Syrphid abundance did vary among orchard sites ($F = 4.45_{5,24}$, $P = 0.0052$) (Fig. 1B), but not between reduced-risk and standard pest management programs ($F = 1.42_{1,24}$, $P = 0.25$) (Fig. 2B). There was no significant interaction effect of site and program on syrphid abundance ($F = 0.92_{5,24}$, $P = 0.48$). Rarefaction curves showed no difference (based on overlapping confidence intervals) in syrphid species richness between pest management programs (Fig. 5A), however, similar to the bee results, rates of syrphid species accumulation varied more widely among orchard sites (Fig. 5B).

Syrphid species arrays were found to vary significantly between

Table 2
Species list of bees and syrphids collected from study sites in Pennsylvania (2007–2009). Total abundance and percent of total abundance[a] are also included for each species.

Species name	Author	Total	Percent total
Andrenidae			
Andrena arabis	Robertson	2	0.07
Andrena barbara	Bouseman & LeBerge	1	0.04
Andrena bisalicis	Viereck	1	0.04
Andrena carlini	Cockerell	36	1.34
Andrena ceanothi	Viereck	2	0.07
Andrena commoda	Smith	7	0.26
Andrena crataegi	Robertson	5	0.19
Andrena cressonii	Robertson	50	1.87
Andrena distans	Provancher	2	0.07
Andrena dunningi	Cockerell	4	0.15
Andrena erigeniae	Robertson	7	0.26
Andrena forbesii	Robertson	5	0.19
Andrena hippotes	Robertson	2	0.07
Andrena imitatrix	Cresson	4	0.15
Andrena melanchroa	Cockerell	1	0.04
Andrena miserabilis	Cresson	3	0.11
Andrena nasonii	Robertson	34	1.27
Andrena perplexa	Smith	5	0.19
Andrena pruni	Robertson	2	0.07
Andrena tridens	Robertson	2	0.07
Andrena vicina	Smith	6	0.22
Andrena violae	Viereck	303	11.31
Apidae			
Anthophora abrupta	(Say)	1	0.04
Anthophora bomboides	Cockerell	1	0.04
Bombus bimaculatus	Cresson	7	0.26
Bombus fervidus	Fabricius	1	0.04
Bombus impatiens	Cresson	23	0.86
Bombus perplexus	Cresson	6	0.22
Bombus vagans	Smith	6	0.22
Ceratina calcarata	Robertson	142	5.30
Ceratina dupla	Say	292	10.90
Ceratina mikmaqi	Rehan & Sheffield	13	0.49
Ceratina strenua	Smith	11	0.41
Eucera hamata	(Bradley)	2	0.07
Habropoda laboriosa	(F.)	1	0.04
Melissodes bimaculata	(Lepeletier)	31	1.16
Melissodes desponsa	Smith	8	0.30
Melitoma taurea	(Say)	2	0.07
Nomada articulata	Smith	1	0.04
Nomada australis	Mitchell	1	0.04
Nomada composita	Mitchell	1	0.04
Nomada cressonii	Robertson	9	0.22
Nomada illinoensis	Robertson	3	0.11
Nomada lepida	Cresson	1	0.04
Nomada luteoloides	Robertson	1	0.04
Nomada maculata	Cresson	1	0.04
Nomada ovata	(Robertson)	1	0.04
Nomada pygmaea	Cresson	3	0.11
Peponapis pruinosa	(Say)	186	6.95
Xylocopa virginica	(L.)	1	0.04
Colletidae			
Hylaeus affinis	(Smith)	28	1.05
Hylaeus mesillae	(Cockerell)	4	0.15
Hylaeus modestus	Say	16	0.60
Halictidae			
Agapostemon splendens	(Lepeletier)	1	0.04
Agapostemon texanus	Cresson	3	0.11
Agapostemon virescens	(F.)	220	8.22
Augochlora pura	(Say)	111	4.14
Augochlorella aurata	(Smith)	198	7.39
Halictus confusus	Smith	35	1.31
Halictus ligatus	Say	58	2.17
Halictus rubicundus	(Christ)	3	0.11
Lasioglossum acuminatum	McGinley	1	0.04
Lasioglossum admirandum	(Sandh.)	7	0.26
Lasioglossum anomalum	(Robertson)	1	0.04
Lasioglossum birkmanni	(Crawford)	2	0.07
Lasioglossum bruneri	(Crawford)	2	0.07
Lasioglossum callidum	(Sandhouse)	3	0.11
Lasioglossum cattellae	(Ellis)	1	0.04
Lasioglossum coriaceum	(Smith)	3	0.11
Lasioglossum cressonii	(Robertson)	2	0.07
Lasioglossum ephialtum	Gibbs	12	0.45
Lasioglossum foxii	(Robertson)	5	0.19
Lasioglossum hitchensi	Gibbs	37	1.38
Lasioglossum illinoense	(Robertson)	1	0.04
Lasioglossum imitatum	(Smith)	47	1.76
Lasioglossum katherineae	Gibbs	1	0.04
Lasioglossum laevissimum	(Smith)	3	0.11
Lasioglossum leucozonium	(Schrank)	1	0.04
Lasioglossum lineatulum	(Crawford)	2	0.07
Lasioglossum macoupinense	(Robertson)	1	0.04
Lasioglossum obscurum	(Robertson)	6	0.22
Lasioglossum paradmirandum	(Knerer & Atwood)	1	0.04
Lasioglossum pectorale	(Smith)	19	0.71
Lasioglossum perpunctatum	(Ellis)	6	0.22
Lasioglossum pilosum	(Smith)	86	3.21
Lasioglossum planatum	(Lovell)	3	0.11
Lasioglossum platyparium	(Robertson)	1	0.04
Lasioglossum quebecense	(Crawford)	1	0.04
Lasioglossum rohweri	(Ellis)	1	0.04
Lasioglossum tegulare	(Robertson)	310	11.58
Lasioglossum trigeminum	Gibbs	3	0.11
Lasioglossum truncatum	(Robertson)	9	0.34
Lasioglossum versans	(Lovell)	1	0.04
Lasioglossum versatum	(Robertson)	5	0.19
Lasioglossum viridatum	(Lovell)	1	0.04
Lasioglossum weemsi	(Mitchell)	3	0.11
Lasioglossum zephyrum	(Smith)	6	0.22
Sphecodes antennariae	Robertson	1	0.04
Sphecodes atlantis	Mitchell	4	0.15
Sphecodes banksii	Lovell	1	0.04
Sphecodes carolinus	Mitchell	11	0.41
Sphecodes solonis	Graenicher	2	0.07
Megachilidae			
Coelioxys alternata	Say	1	0.04
Heriades carinatus	Cresson	1	0.04
Hoplitis producta	(Cresson)	1	0.04
Hoplitis truncata	(Cresson)	1	0.04
Megachile addenda	Cresson	1	0.04
Megachile brevis	Say	1	0.04
Megachile gemula	Cresson	1	0.04
Megachile melanophaea	Smith	1	0.04
Megachile mendica	Cresson	3	0.11
Osmia atriventris	Cresson	5	0.19
Osmia bucephala	Cresson	13	0.49
Osmia cornifrons	(Radosz.)	7	0.26
Osmia georgica	Cresson	2	0.07
Osmia pumila	Cresson	103	3.85
Osmia taurus	Smith	7	0.26
Stelis coarctatus	Crawford	2	0.07
Stelis lateralis	Cresson	1	0.04
Syrphidae			
Allograpta obliqua	(Say)	9	0.5
Blera badia	(Walker)	1	0.1
Chrysotoxum pubescens	Loew	1	0.1
Epistrophe grossulariae	(Meigen)	1	0.1
Eristalis hirta	Loew	1	0.1
Eristalis tenax	(L.)	3	0.2
Eupeodes americanus	(Wied.)	54	3.1
Ferdinandea buccata	(Loew)	2	0.1
Heringia calcarata	Loew	74	4.3
Melanostoma mellinum	(L.)	21	1.2
Merodon equestris	(F.)	1	0.1
Myolepta varipes	Loew	2	0.1
Parhelophilus obsoletus	(Loew)	2	0.1
Platycheirus immarginatus	(Zett.)	4	0.2
Pseudodorus clavatus	(F.)	1	0.1
Pterallastes thoracicus	Loew	7	0.4
Rhingia nasica	Say	2	0.1
Sphaeropharia contigua	Macquart	8	0.5
Syritta pipiens	L.	1	0.1
Syrphus rectus	Osten	1	0.1
Syrphus torvus	Osten	2	0.1
Toxomerus geminatus	(Say)	639	36.9

Table 2 (*continued*)

Species name	Author	Total	Percent total
Toxomerus marginatus	(Say)	889	51.3
Xylota ejuncida	Say	5	0.3
Xylota quadrimaculata	Loew	3	0.2

[a] Percent total was calculated for bees and syrphids separately.

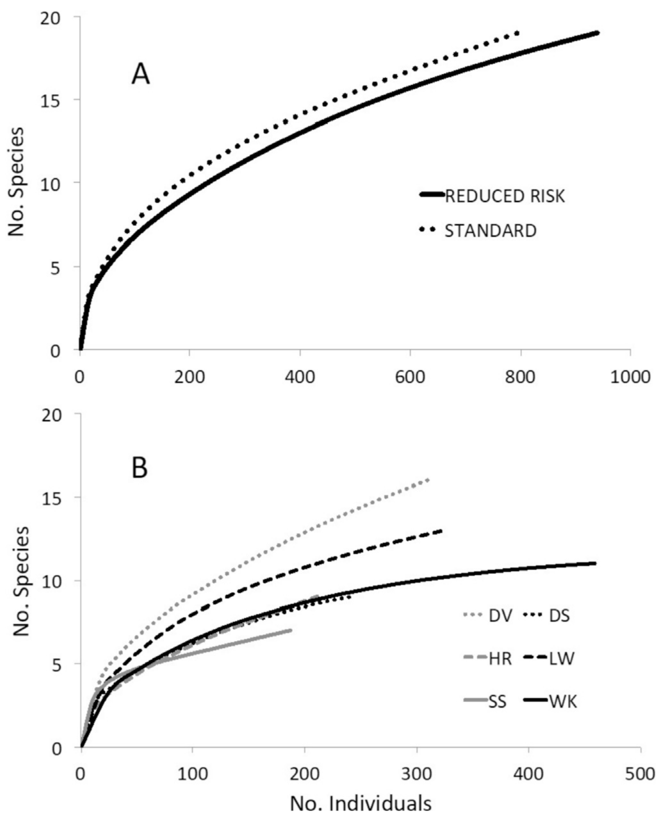

Fig. 5. Individual-based rarefaction curves depicting syrphid species accumulation in apple orchards from 2007 to 2009. Syrphid species accumulation is compared (A) between reduced-risk and conventional standard pesticide programs, and (B) among the six research sites (abbreviations based on the names of the commercial farms).

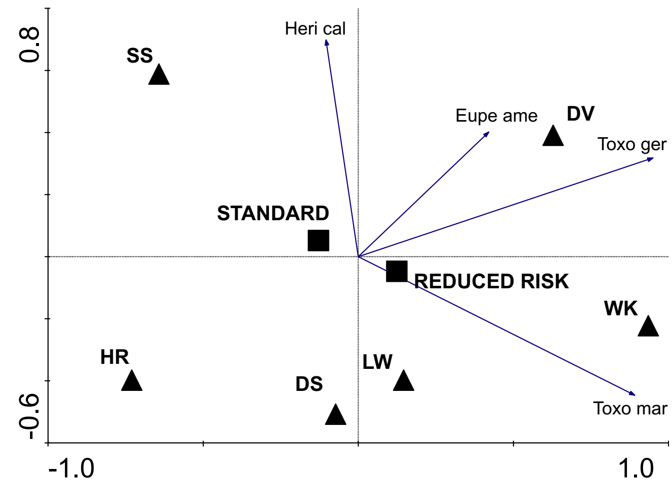

Fig. 6. RDA biplot depicting associations among abundant syrphids (vectors), pest management programs (squares), and orchard sites (triangles; abbreviations based on names of the commercial farms). Species names are abbreviated; full names can be found in Table 2.

orchard locations, with the DV site ($F = 5.86$, $P = 0.002$) differing from other locations along the first axis (Fig. 6). There was no significant difference in community assemblages between pest management programs ($F = 0.98$, $P = 0.458$) (Fig. 6).

4. Discussion

Non-pest arthropod species in fruit orchards are inevitably influenced by a combination of crop management practices and the surrounding landscape at various scales. Among the pollinators, there are over 50 species of insects including bees and syrphids that are present during apple bloom (Biddinger et al., 2018; Joshi et al., 2016). Apple and other fruit growers have increasingly relied on wild bees for most of their pollination needs because ongoing high annual losses of commercially managed honey bee colonies (Kulhanek et al., 2017) has reduced their availability and quality, and increased rental costs, calling for wild pollinator conservation to be a key component of integrated pest management programs in fruit crops such as apple (Biddinger and Rajotte, 2015; Joshi et al., 2011; Park et al., 2010; Ritz et al., 2012).

In this multiyear study, we found that the implementation of reduced-risk insecticide programs in commercial apple orchards greatly reduced the pesticide active ingredient use per hectare and resulted in significantly lower environmental impacts compared to conventional standard pesticide programs. Despite the reductions in pesticide load and environmental impact in the reduced-risk program, we did not find differences in abundance or species richness of bees and syrphids between the two management systems. However, the reduced-risk program did employ greater use of neonicotinoids, some of which are a concern regarding their non-target effects on pollinators (Feltham et al., 2014; Goulson, 2013). Despite the difficulty in detecting field-relevant effects of neonicotinoids (Blacquière et al., 2012), some evidence from other cropping systems has shown that neonicotinoids can affect pollinator health and performance under realistic field conditions (Tsvetkov et al., 2017), although results could vary from one location to another (Woodcock et al., 2017) Therefore, despite the lower EIQ values for the reduced-risk program, we did not detect significant field relevant impacts on bee and syrphid pollinators between the two programs. The increased use of neonicotinoids in the reduced-risk programs, may have offset potential gains in pollinator diversity within these systems, explaining our inability to detect significant differences in bee diversity and assemblages between the two pest management programs, but the reduced risk program did not do any worse than the conventional program in terms of impacting the pollinator community.

While other studies have been able to document differences in bee diversity among different farm management systems in other crops (e.g., Holzschuh et al., 2007; Morandin and Winston, 2005), we could not find differences between reduced-risk and conventional pesticide programs in the commercial apple orchards. This pattern was not consistent for other arthropod groups in commercial tree fruit; earlier studies, including one in the same region, found that reduced-risk programs in peach supported more robust communities of arthropod predators and parasitoids, as compared to conventional programs (Atanassov et al., 2003; Biddinger et al., 2014). In this case, certain predators and parasitoids may be less mobile and more intimately associated with the crop and its hosts, thereby increasing the chance of pesticide exposure, explaining the negative response to the conventional management system.

The lack of differences in abundance and species richness of bees under both types of pest management programs could be due to several interacting factors in the apple orchard ecosystem. For instance, we have not observed, and consider it unlikely, that wild bees are nesting in the commercial orchards due to a lack of nesting sites for cavity nesting species and the continued contamination of the soil by the extensive use of pesticides, including herbicides. Based on detailed evaluations of the plant diversity in and adjacent to these orchards, where plant diversity was strongly correlated with bee diversity and abundance, we believe the differences we found in bee community structure between sites is likely due to differences in adjacent plant diversity and nesting sites in the local landscape (Kammerer et al., 2016a; Kammerer et al., 2016b). In a similar study in New York apple orchards, Park et al. (2015) found that the negative effects of pesticides across a gradient of conventional orchards were buffered by the adjacent natural and semi-natural landscape in close proximity to the orchards evaluated. Notably, studies that have found effects due to farm management practices (e.g., Holzschuh et al., 2007; Morandin and Winston, 2005) also cite landscape context as a dominant factor influencing bee diversity and abundance.

Abundance of syrphids in apple orchards is primarily dependent on the presence of other insects such as aphids, as the larval stages of the majority of the syrphid species we found are predators. Some of the most abundant syrphid species we found [i.e. *Eupeodes americana* (Weidemann), several species of *Syrphus*, and *Heringia calcarata* (Leow)] are the main biological control agents of woolly apple aphid (*Eriosoma lanigerum* (Hausmann)), green apple aphid [*Aphis pomi* (De Geer)], and spirea aphid (*Aphis spiraecola* Patch), which are important pests of apple in this region. Only adult syrphids forage on flowers for pollen and nectar. It is likely that both pest management programs had similar effect on the population dynamics of aphids in apple orchards, and therefore differences in the abundance of adult syrphids between pesticide programs were not observed. Or, the larval prey were not very abundant in the orchards and the captured adult syrphids only represented transient visitors feeding at apple blossoms, remaining relatively unaffected by pesticide applications. Biddinger et al. (2014) also found that syrphids did not show a strong association with either conventional or reduced-risk pesticide programs in peach. However, the role of other factors such as availability of alternate prey, competition with other natural enemies, plant diversity and landscape heterogeneity are probably also important.

Abundance and species richness of wild bees are generally influenced by surrounding landscape, including forested patches adjacent to apple orchards (Watson el., 2011). Natural or semi-natural habitat in landscapes surrounding apple orchards have been reported to act as a buffer in minimizing the effect of pesticide use on abundance and species richness of wild bees in New York region (Park et al., 2015). In Pennsylvania apple-growing regions, the landscape is very diverse, and includes forested patches, farms with other fruit crops (e.g., peach, pear, cherry, and nectarines), field crops (e.g. corn and soybean), vegetables, and open patches of wild flowering plants. Such diversity in the landscape might provide adequate nesting habitats and floral food resources for wild bees and syrphids. Considering the orchard site effect, we found a significant variation in the abundance and richness of pollinators across orchard locations. Surrounding landscape, floral resources and the presence of different nesting habitats adjacent to apple orchards varies from one location to other, and it could be the main factor causing such variability (Watson et al., 2011; Kammerer et al., 2016a; 2016b; Kallioniemi et al., 2017). However, irrespective of location, impact of reduced-risk and conventional pesticide programs on bee and syrphid abundance and richness was statistically similar for the entire study period. This suggests that these pollinators are not affected by the field relevant conditions of pesticide applications in this type of landscape, or that mortality to adult bees and to the returning populations each year was similar across both types of pesticide programs.

Although we did not find major differences in species assemblages between programs, we stress the importance of species-level identification in pollinator research, as differences in abundance of specific species could indicate increased susceptibility and mortality of certain bees to specific pesticides or the timing of applications. For example, we have found that applications of several neonicotinoid insecticides is present at significant, but low levels in the nectar and pollen of apple blossoms when applied prebloom at the pink developmental stage prior to bloom when used to control of rosy apple aphid (*Dysaphis plantaginea* Passerini). However, applying the same pesticides approximately 10 days earlier reduces these levels below detection limit while still controlling the aphids (Biddinger unpublished data).

In the U.S., the Food Quality Protection Act has largely eliminated the use of organophosphate and carbamate insecticides in favor of biological control, pheromone-based management systems and 'softer' pesticides (with low toxicity and impact on non-target species, human and environmental health) resulting in 'reduced-risk' IPM programs (Whalon et al., 1999). Selectivity for target pests is one of the major benefits of using reduced-risk pesticides, and due to selective mode of action for target pest, reduced-risk pesticides usually require lower rates for field application, and have become widely popular in integrated pest management programs for several economically important crops. Reduced-risk programs in fruit crops, which drastically reduce organophosphate, carbamate and pyrethroid use, provide optimal and comparable pest control to conventional programs and have significantly better EIQ ratings (Agnello et al., 2009; Biddinger et al., 2014). Reduced-risk programs in other crops have been linked with other ecological benefits as well. For instance, in a multiyear study, Biddinger et al. (2014) found that the beneficial arthropods (such as predators and parasitoids) were more highly associated with reduced-risk pesticide programs than the conventional pesticide programs in commercial peach orchards. Similar ecological benefits of adopting reduced-risk pesticide program have been reported elsewhere (Atanassov et al., 2002, 2003), while other studies have shown mixed results. For example, within reduced-risk IPM programs some neonicotinoid and IGR insecticides have been shown to have negative effects on coccinellid predators of mites and parasitic hymenoptera in the tree fruit orchards (Biddinger and Hull, 1995; Brunner et al., 2001), while promoting biological control of phytophagous pest mites by predatory Phytoseiid mites (Biddinger et al., 2009).

Biodiversity of wild pollinators is generally higher in apple and other fruit growing farms in the northeastern US (Park et al., 2010; Joshi et al., 2015) than many other agroecosystems, mainly due to local landscape characteristics and related factors, although diversity may vary over time as well as location to location (Joshi et al., 2015). In Pennsylvania, out of 371 reported bee species (Donovall and vanEngelsdorp, 2010), we have net-collected 54 species of wild bees and 6 species of syrphids on apple bloom (Biddinger et al., 2018). Bee diversity and abundance for the entire crop season, including bloom, was similar to our other studies conducted in commercial orchards with similar landscape features in this region (Joshi et al., 2015).

In summary, reduced-risk and conventional pest management programs similarly influence the diversity and abundance of bees and syrphids in commercial apple orchards despite the significant reduction in pesticide inputs (in terms of total active ingredient per hectare) in the reduced-risk programs. Differences in bee and syrphid diversity and assemblages among study sites, but no differences between the pest management programs, suggest the site-specific importance of farm landscape, diversity of floral plants, and nesting sites. Though the role of these landscape factors in influencing pollinator biodiversity and abundance in tree fruit have been studied in the past, field studies that document changes in community composition and population dynamics due to changes in IPPM programs and the use of new pesticide chemistries, could be an important aspect of future research into wild pollinators conservation on crops and regions where they are economically important.

Conflicts of interest

The authors declare no competing financial interests.

Acknowledgements

The authors are thankful to the USDA–CSREES RAMP (2006-51101-03604) and USDA-SCRI (PEN04398) for financial support. Authors are also thankful to the orchard owners: J. Lerew, S. Slaybaugh, D. Wenk, D. Harner, C. Harner, D, Slaybaugh and E. Diveley Jr. for allowing us to conduct this multi-year study in their commercial orchards, and summer research assistants B. Wenk, C. Altimose, and J. Lee for assisting in fieldwork. We also thank various agricultural chemical companies for donation of various pest management products used in this study, and J. Gibbs, K. Wright, R. Jean, L. Donovall and S. Droege for technical help with bee identification, and C. Thompson for technical help with identification of syrphid specimens. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the view of the U.S. Department of Agriculture.

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