

Floral Strips Attract Beneficial Insects but Do Not Enhance Yield in Cucumber Fields

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Abstract

Natural enemies and pollinators require nutritional and habitat resources that are often not found in conventional agricultural fields. The addition of flowering plants within agroecosystems may provide the resources necessary to support beneficial insects at the local scale. We hypothesized that insect pollinator and natural enemy abundance would increase in cucumber (*Cucumis sativus*) plots containing flower strips and that the effect would be greatest in the crop rows closest to the flower strips. Three flower treatments were tested: 1) buckwheat (*Fagopyrum esculentum*), 2) yellow mustard (*Brassica hirta*), 3) sweet alyssum (*Lobularia maritima*), and cucumbers as a control. Flowers were planted within a commercial cucumber field in 20-m-long strips in a randomized complete block design with six replications in the 2014 and 2015 growing seasons. Some floral treatments successfully attracted more beneficial insects than others, but the beneficials did not disperse out to the cucumber plants. Cucumber yield was unaffected by flowers with one exception: in 2015, cucumber yield in the sweet alyssum plots were greater than those in plots with no flowers. Our research indicates that adding flowers to cucumber fields to increase services from beneficial insects needs to be further investigated to better understand the effect of factors such as relative flowering strip size.

Key words: insectary plant, floral intercropping, habitat diversification, bee, farmscaping

The simplification of plant diversity in agroecosystems has negative impacts, such as pest outbreaks and reduced ecosystem services from beneficial organisms (Landis et al. 2000, Goverde et al. 2002, Carvell et al. 2006). Increasing plant diversity with flowering plants within or near fields is one way to mitigate undesirable effects of monocultures, with the ultimate goal of providing more and higher quality resources for natural enemies and pollinators (Costello and Altieri 1995, Langellotto and Denno 2004, Letourneau et al. 2011, Nicholls and Altieri 2013). Growers have control over within-field management of resources, as opposed to changing the landscape around their farms. Increasing plant or habitat diversity on a local scale is of interest to many farmers, especially given that government subsidies exist in the United States and Europe to implement such practices (Kleijn et al. 2007, Batáry et al. 2015). Although public awareness of the potential positive effects of flowers in or near crop fields is increasing, there is a lack of scientific information on how best to put these into practice to support higher crop yield (Haaland et al. 2011).

Attracting pollinators and maximizing their efficacy in agroecosystems has gained attention due to the current decline of managed bees (Petersen et al. 2013, Shackelford et al. 2013, Garibaldi et al. 2014, Giannini et al. 2015, Goulson et al. 2015, Winfree et al.

2015). Bees are sensitive to disturbance due to environmental changes or human activity and require food and other resources that are reliably available throughout the growing season (Williams et al. 2010, Winfree et al. 2011). Placing floral and nesting resources near or into cropped areas can help provide resources needed by bees (Haaland et al. 2011, Kennedy et al. 2013, Morandin et al. 2014). Most vegetables are annual crops, and growers face challenges for managing pollinators owing to intense plant management regimes in these systems. For example, the crop field is typically rotated to a new location every year, planting is preceded by plowing, and plants are intensively managed with insecticides and other cultural controls during the growing season, as is the case with cucurbits.

In cucumbers (*Cucumis sativus*, Cucurbitaceae), bee pollination is essential for fruit set. Cucumbers are dioecious, and inadequate pollination can lead to fruit abortion and distortion (McGregor 1976, Stanghellini et al. 1997). Cucumber flowers are relatively small, lack nectar resources, and are hidden beneath the leaf canopy; they are relatively unattractive to many bees (Cook et al. 2003, Peng et al. 2004). In the Midwestern United States, the most common pollinators of cucumbers are honey bees (*Apis mellifera* L., Hymenoptera: Apidae) and the common eastern bumble bee (*Bombus impatiens* Cresson, Hymenoptera: Apidae), but the role of

other pollinators in this system is not well understood (Smith et al. 2013). The addition of managed honey bee hives adjacent to or within cucurbit fields does not necessarily increase their abundance at flowers (Shuler et al. 2005), indicating that honey bees are not the best pollinators for this crop. Wild pollinators have demonstrated higher pollination rates than managed bees in several cases in cucurbits and other crops (Artz and Nault 2011, Gajc-Wolska et al. 2011, Holzschuh et al. 2012, Garibaldi et al. 2013, Blaauw and Isaacs 2014). Many wild bees that visit cucumber and other crops are ground nesting and prefer to nest adjacent to or among their preferred host plants (Julier and Roulston 2009, Lonsdorf et al. 2009, Roulston and Goodell 2011); thus, adding undisturbed seminatural habitats or flowers to cucumber fields is expected to increase wild bee abundance and diversity within the field. Bees are central place foragers, meaning that the location of nesting habitat relative to the crop is important (Lonsdorf et al. 2009, Morandin and Kremen 2013). Therefore, the spatial relationship of flower enhancement and crop is important to take into account. Taken together, the literature suggests that habitat management may enhance pollination in cucumbers, but further investigation is needed.

Most habitat management methods targeted at increasing floral diversity for pollinators are also ideal for enhancing the abundance of predators and parasitoids seeking nectar and pollen. As with pollinators, conventional management practices often harm natural enemies through insecticide exposure and lack of habitat diversity at the local scale (Carmona and Landis 1999, Landis et al. 2000, Desneux et al. 2007). Natural enemies can provide significant levels of pest control in cucurbits and other systems when they are present in sufficient numbers (Root 1973, Hooks et al. 1998, Fiedler et al. 2008, Phillips and Gardiner 2016). In zucchini fields, increased non-crop vegetation led to improved pest control and natural enemy abundance in cropped areas (Hinds and Hooks 2013), and control of squash bugs by carabids and spiders was improved in squash fields with increased structural complexity (Snyder and Wise 2008). In general, patches of floral resources inside or adjacent to agricultural fields tend to enhance beneficial activity and provide pest suppression (Chaplin-Kramer et al. 2011, Kennedy et al. 2013, Blaauw and Isaacs 2014).

We measured the effects of floral provisioning on beneficial insect abundance and crop yield in commercial cucumber fields in two growing seasons. We predicted that the inclusion of flower strips in cucumber fields would increase abundance of natural enemies and pollinators on cucumber flowers and increase cucumber yield and quality (grade). The effect of flower strips on beneficial insects was expected to be the strongest in rows of cucumbers adjacent to flowers.

Materials and Methods

Field Plots

The experiment took place in commercial cucumber fields in Benton Harbor, MI, in 2014 and 2015. The fields were 201 by 402 m in 2014 and 183 by 366 m in 2015. Major field activities are summarized in Supp. Table 1 (online only), including the grower's pest management practices. A randomized complete block design was implemented; the field was divided into six blocks with the following four treatments (Fig. 1A): 1) *Brassica hirta* (yellow mustard, 'Tilney'); 2) *Lobularia maritima* (sweet alyssum, 'Carpet of Snow'); 3) *Fagopyrum esculentum* (buckwheat); and 4) a slicing cucumber control treatment. The flower species were chosen because they are known to attract pollinators and natural enemies (Fiedler et al. 2008). Slicing cucumbers (*Cucumis sativus*, 'Intimidator') were

planted at the end of April on black plastic with drip fertigation in both years, with an at-planting drench application of imidacloprid insecticide. For the flower strips, the black plastic was removed in 20-m-long sections that were separated by 40 m in rows and 12 rows (~50 m) between flower strips (Fig. 1A). Slicing cucumber control plots of the same dimension were randomized within each replicate, and managed according to grower practice. Cucumber seeds were hand planted and promptly covered with low tunnels using a transparent plastic cover. Sweet alyssum was hand seeded, whereas buckwheat and mustard were seeded with a Model JP-3 Clean Seeder using a Y24 disk for mustard and a R12 disk for buckwheat (Jang Automation Co., Ltd, South Korea). Oats were used as a nurse crop for the alyssum in 2014. At the end of May 2014, the oat nurse crop was killed with a selective herbicide application and low tunnels were removed. A single pyrethroid application occurred in June in both years to control insect pests. Managed honey bees were stocked at two hives per acre adjacent to the field in both years. In late June and July, cucumbers were harvested in both years.

Insect Sampling

Yellow sticky traps (12 by 15 cm, Great Lakes IPM, Vestaburg, MI) were deployed at the center of each flower strip (one per flower strip) at canopy height in 2014 and 2015. In addition, in 2015, one sticky trap was also deployed in Row 3 (Fig. 1B). Traps were changed weekly from plant emergence to end of harvest (4 wk per year). Traps were frozen at -20°C and arthropods on traps were identified in the laboratory to Order or Family. Flower strips were sampled weekly via sweep net by sweeping each 20-m strip 100 times.

Sampling for pollinators occurred between 0730 hours and 1230 hours on sunny, calm days, at ~1-wk intervals starting at about 10% bloom. In 2014 and 2015, in the cucumbers, pollinators were assessed visually by walking parallel to the floral strip and recording the number and identity of all bees observed over a 10-min period. Sampling transects (0.77 by 20 m) were located 1.5 m (Row 1), 5 m (Row 3), and 10 m (Row 5) away from the flower strips in the cucumber field (Fig. 1B). In 2015, pollinators were observed also within the flower strips (Row 0). If sight identification was not possible, pollinators were collected by insect nets and insect vacuums (BioQuip, Rancho Dominguez, CA) for laboratory identification. In the laboratory, pollinators were pinned and identified (Mitchell 1960, 1962; Ascher and Pickering 2016).

Representative voucher specimens of arthropods that were collected as part of this project are kept at Michigan State University's A.J. Cook Arthropod Collection, East Lansing, MI.

Yield

Cucumber yield data were collected twice during harvest on July 1 and July 10 in 2014 and July 8 and July 15 in 2015. All cucumbers with length >12.5 cm were harvested from a 1-m section within the same transects used for sampling pollinators (1.5, 5, and 10 m away from flowering strips). Cucumbers were categorized by grade according to their diameter and length in accordance with the United States Standards for Grades of Cucumbers. Total marketable yield for each transect was obtained for each plot by summing the fresh weights of cucumbers from all grades.

Statistical Analyses

Arthropod abundance by taxonomic group, sampling method, treatment, and row were analyzed with generalized linear mixed models using a Poisson distribution, with treatment and row as independent variables and treatment as the main effect. Date was nested within

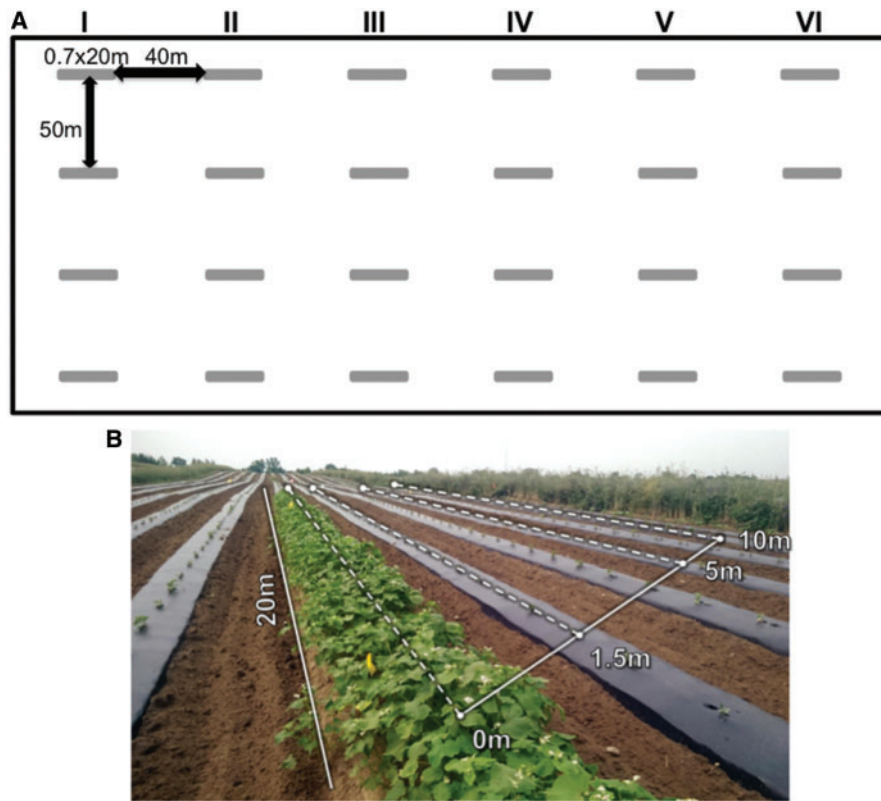


Fig. 1. Top down view of the ~8-ha commercial cucumber field showing distances between flower strips (gray dashed lines) (A). Flower strips were set up in a randomized complete block design ($N=6$) in 2014 and 2015. Cucumber rows are not indicated on the map; roman numerals at the top denote blocks with four flower strip treatments. Photo of an experimental unit for measuring the impact of flower strips on beneficial insects in a commercial cucumber fields (B). Sampling transects (0.77 by 20 m) were composed of the entire flower strip (Row 0), 1.5 m (Row 1), 5 m (Row 3), and 10 m (Row 5) away from the flowers in the cucumber rows parallel to the flower strips.

block as a random effect. Where main effect was significant ($\alpha=0.05$), pairwise Tukey–Kramer adjusted least-square means tests were performed (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC). Most Diptera were excluded from the analysis, except for Tachinidae and Syrphidae.

We analyzed cucumber weight and average grade at harvest within the transects by distance from the flowering strips with generalized linear mixed models using a normal distribution, rows as independent variables, and treatment as the main effect. Treatment was nested within block as a random effect. Where main effect was significant ($\alpha=0.05$), pairwise Tukey–Kramer adjusted least-square means tests were performed (PROC GLIMMIX).

Results

Sticky Traps

In 2014, in total, 2,796 insects were collected and identified on 130 sticky traps deployed in the flower strips. The number of traps was increased to 229 traps in 2015 when a total of 6,652 insects were collected by sticky trap, 42% more than in 2014. In total, 115 sticky traps were collected from the flower strips in 2015, with 5,132 insects collected on these traps. In the third row of cucumbers away from the flower strips, in total, 114 sticky traps were deployed, catching a total of 1,521 insects. There were no significant treatment effects on the number of arthropods in any of the herbivorous taxa on sticky traps in 2014 ($F_{4,115} < 1.95$, $P > 0.05$) or 2015 ($F_{3,206} < 0.98$, $P > 0.05$).

In 2014, before and during harvest, the abundances of lady beetles (Coccinellidae) and minute pirate bugs (*Orius* spp.) collected by sticky trap in the floral strips were significantly different among treatments (Coccinellidae: $F_{4,93} = 2.7$, $P < 0.05$; *Orius* spp.: $F_{4,93} = 3.39$, $P < 0.05$; Fig. 2A). Significantly more lady beetles were found on the sticky traps in the buckwheat and sweet alyssum strips than control cucumber plots ($t > 1.32$, $df = 93$, $P < 0.05$; Fig. 2A). Significantly more minute pirate bugs were found on sticky traps placed in mustard and sweet alyssum strips compared with control cucumber plots ($t > 3.32$, $df = 93$, $P < 0.05$).

In 2015, flower treatment ($F_{3,206} = 137.04$, $P < 0.01$; Fig. 2B) and distance from flower strip ($F_{3,206} = 241.83$, $P < 0.01$) significantly affected the number of minute pirate bugs on sticky traps. Minute pirate bugs were more abundant in the mustard flower strips than in the alyssum and control strips ($t > 31.57$, $df = 206$, $P < 0.01$). Flower treatment ($F_{3,206} = 196.25$, $P < 0.01$) and distance from flower strip ($F_{3,206} = 61.44$, $P < 0.01$) significantly affected parasitoid abundance on sticky traps. Parasitoids were more abundant in the mustard and alyssum strips compared with other treatments and rows ($t > 31.57$, $df = 206$, $P < 0.01$). They were also significantly more abundant in the cucumber areas near buckwheat flower strips than in or near the other flower treatments ($t > 12.49$, $df = 206$, $P < 0.01$). All other natural enemy taxa were not significantly affected by treatment, row, or their interaction ($F_{3,206} < 0.77$, $P > 0.05$).

Sweep Net

In 2014, in total, 2,863 arthropods were collected and identified from 90 sweep net samples collected from the flower strips over a

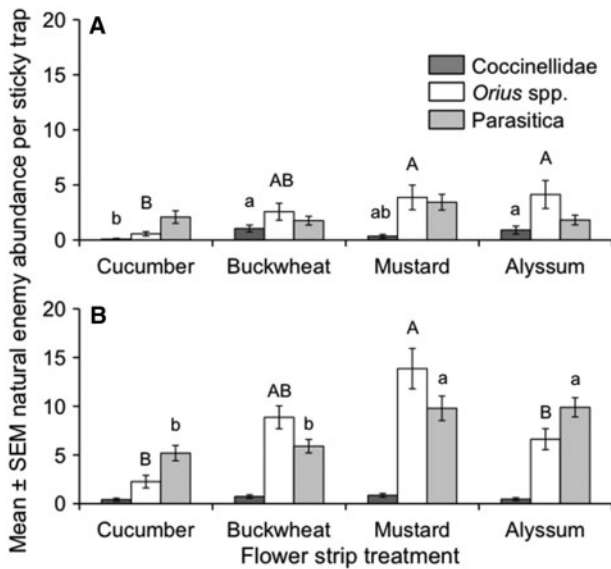


Fig. 2. Mean (\pm SEM) number of lady beetles (*Coccinellidae*), minute pirate bugs (*Orius* spp.), and parasitoids (*Parasitica*) observed on 12- by 15-cm sticky traps in the flower strips (Row 0) before and during cucumber harvest by flower treatment in 2014 (A) and 2015 (B). Traps were collected and replaced weekly. Bars with different letters of the same case indicate significant differences (Tukey's HSD, $\alpha = 0.05$).

5-wk sampling period. Transects in sweet alyssum yielded nearly half (47.6%) of all arthropods collected using this method ($n = 1,363$). In 2015, a total of 90 sweep samples were collected from the flower strips over a 5-wk sampling period, with 3,629 arthropods collected. The greatest abundance of arthropods in 2015 was found in samples from mustard ($n = 1,494$), followed by sweet alyssum ($n = 1,076$), and buckwheat ($n = 1,059$). Flowering treatment did not significantly affect the weekly or seasonal abundance of arthropods collected by sweep net from the flower strips before or during cucumber harvest in 2014 ($F_{3,70} < 0.21$, $P > 0.05$) or 2015 ($F_{3,78} < 0.01$, $P > 0.05$).

Pollinator Observation

In total, 478 pollinators were observed on cucumber plants in 2014. In 2014, flowering treatment, row, and the interaction between treatment and row was not significantly different for observed pollinators among rows 1, 3, or 5 away from the flower treatments ($F_{6,184} < 1.54$, $P > 0.2$).

In the flower strips that were sampled in 2015, pollinators were visually surveyed in both the flower strips and the cucumbers for a total of 5,068 observed pollinators. Of those, in total, 767 pollinators were observed on cucumber plants. No significant differences were found in either year for the number of bees observed 1, 3, or 5 rows away from the flower treatments before cucumber harvest ($F_{6,271} < 2.42$, $P > 0.05$). Significantly more honey bees were observed in the flower strips of the mustard and buckwheat treatments than in other rows and treatments ($t > 5.02$, $df = 361$, $P < 0.01$; Fig. 3A). Significantly more syrphids were observed in the alyssum strips compared with buckwheat and mustard strips ($t > -10.66$, $df = 361$, $P < 0.01$), but there were no significant differences in syrphid numbers among any of the rows with cucumbers ($t < 0.34$, $df = 361$, $P > 0.05$; Fig. 3B). Significantly more native bees were observed within the flower strips of the mustard and buckwheat treatments than in other rows and treatments ($t > -25.97$, $df = 361$, $P < 0.01$; Fig. 3C).

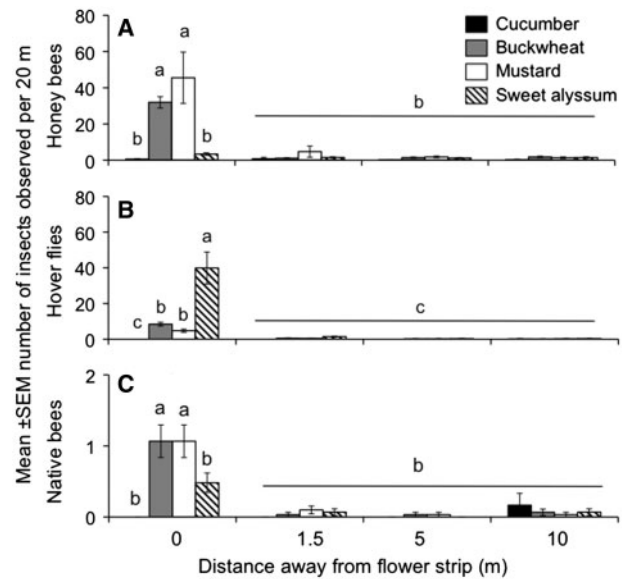


Fig. 3. Mean (\pm SEM) number of honey bees (A), hover flies (B), and native bees (C) observed by transect in 2015. Observations occurred over 10-min periods weekly throughout the growing season in 0.77- by 20-m transects located within the flower strips (Row 0), 1.5 m (Row 1), 5 m (Row 3), and 10 m (Row 5) away from the flower strips. Bars show averages across all distances. Bars with different letters of the same case indicate significant differences (Tukey's HSD, $\alpha = 0.05$).

Yield

In 2014, there were no significant differences among flower treatments or distance from the flower strips in total cucumber fresh weight harvested per m ($F_{2,73} < 2.66$, $P > 0.05$; Fig. 4A), and the interaction between flower treatment and distance was not significant ($F_{8,70} = 0.46$, $P > 0.05$). The percentage of low-grade cucumbers harvested was not affected by treatment ($F_{4,70} = 1.29$, $P > 0.05$), distance from flower treatment ($F_{2,70} = 1.48$, $P > 0.05$), or their interaction ($F_{8,70} = 0.46$, $P > 0.05$).

In 2015, cucumber yields were significantly greater near sweet alyssum compared with the cucumber control treatments ($t > -2.69$, $df = 122$, $P < 0.01$, Fig. 4B). Cucumber yields were greater in Row 5, the row furthest away from the floral strips, compared with Row 1 ($t > -2.64$, $df = 122$, $P < 0.03$). The interaction between treatment and row did not significantly affect mass harvested ($F_{6,122} = 0.28$, $P > 0.05$). No significant differences in mean grade of cucumbers harvested by treatment or row were observed ($F_{6,87} < 0.78$, $P > 0.05$).

Discussion

In conventional agriculture, noncrop flowering plant species are rarely allowed to grow adjacent to or within agricultural fields due to intensive herbicide use, revenue loss from uncultivated space, and competition with the crop. On the other hand, pollinators and natural enemies respond positively to increased local floral availability, suggesting that the addition of flowering resources to agroecosystems can positively affect pollination and biological control (Kremen and Miles 2012, Shackelford et al. 2013, Riedinger et al. 2014). While there is some evidence that the presence of flowers in agroecosystems can increase the abundance and diversity of bees and natural enemies at the field level (Rebek et al. 2005, Wanner et al. 2006, Fiedler et al. 2008, Woodcock et al. 2014), our results do not support these previous reports.

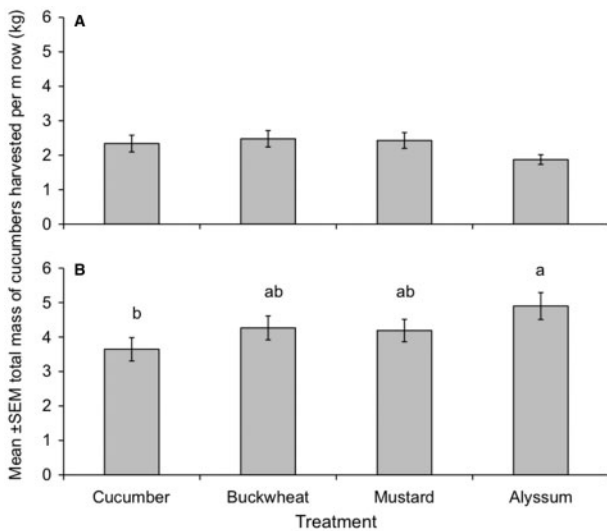


Fig. 4. Mean (\pm SEM) total mass (kg) of cucumbers harvested per m² in 2014 (A) and 2015 (B). Cucumbers were sampled from rows located 1.5, 5, and 10 m away from the flower strips. Bars with different letters of the same case indicate significant differences (Tukey's HSD, $\alpha = 0.05$).

Beneficial Insects

Our experiments did not detect benefits of within-field floral intercropping extending throughout the field. As expected, we detected greater numbers of beneficial insects in the floral strips compared with the cucumbers in both seasons. This was not surprising since the cucumber flowers provide little nectar and pollen (Cook et al. 2003, Peng et al. 2004), whereas the floral species used here are well-established insectary plants high in nectar (Platt et al. 1999, Landis et al. 2000, Berndt and Wratten 2005, Fiedler et al. 2008). It is likely that the flowers we used concentrated the available beneficial insects in the flower strips rather than drawing them into the cucumbers. In our case, cucumber flowers might have been considered low-quality resources relative to flowers in the strips.

Honey bee numbers at cucumber flowers were similar regardless of plant species in the flower strip. This suggests that flower strips did not attract bees away from cucumbers; rather they may have attracted honey bees from surrounding areas to the field. Similarly, honey bee visitation to crop flowers was not affected by flower plantings adjacent to crops compared with mowed grass borders over a 4-yr period; these results indicate that honey bees may not consistently respond to flower enhancements in or near crop fields, although in this case insectary strips bloomed after the crop (Blaauw and Isaacs 2014). While honey bees are generalists, they exhibit a large degree of flower constancy, meaning they will be fixed for many foraging bouts on certain flowers (Grant 1950), which might explain why numbers of bees at cucumber flowers remained unaffected by the presence of flower strips. On the other hand, honey bees and other generalist wild bees are known to prefer to visit flowers with high-quality resources, which would favor switching from cucumber to insectary flowers.

Distance from the flower strips did not significantly affect pollinator foraging on cucumber plants. Pollinators are highly mobile and can cover relatively large distances proportional to their body size in search of their preferred floral resources (Greenleaf et al. 2007, Benjamin et al. 2014, Danner et al. 2014). The distance between rows may have been too small to detect a distance effect, as bees may forage as far as several kilometers away from their nests (Greenleaf and Kremen 2006, Greenleaf et al. 2007, Lonsdorf et al. 2009).

In pickling cucumber, for example, differences in floral visitation were detected in response to landscape level resources as far as 2,000 m from field centers (Lowenstein et al. 2012). In bell pepper and almond, closer proximity to floral resources increased the richness and abundance of visiting bees (Norfolk et al. 2015, Pereira et al. 2015). The lack of spatial response by honey bees in our study is somewhat unexpected, given that diverse hedgerows increased honey bee abundance in tomato fields 10 m away from the field edge compared with weedy unmanaged field edges, demonstrating that these bees can respond positively to habitat enhancements at relatively small spatial scales in California (Morandin and Kremen 2013). Perhaps, there are more alternative resources in temperate Southwestern Michigan where our study was carried out for honey bees to visit, leaving them less dependent on and responsive to our habitat management efforts.

Yield

Habitat management has the potential to increase the abundance and diversity of wild pollinator populations, increasing yield in turn (Garibaldi et al. 2014). In the current study, cucumber yield was significantly affected by the flower treatments in 2015 (Fig. 4B), with the mass of cucumbers from some plots near sweet alyssum being significantly greater than the control plots, although this yield increase was only significant in the cucumber rows furthest away from the alyssum. Cucumbers tend to be variable in size, weight, and shape, and produce fruit for several weeks, during which time cucumbers are harvested daily. Increasing the harvest area of cucumbers collected for yield estimation could provide a more robust assessment of the amount and quality of cucumber yield. Hydration, pollination, nutritional, and varietal differences can all impact the number and quality of cucumbers harvested (Ismail and Ozawa 2007, Bhardwaj and Kumar 2014, Rahil and Qanadillo 2015, Motzke et al. 2015). The interaction of these factors in combination with the fact that pollinator visitation to cucumber plants was not increased by the treatments is a likely explanation for the weak treatment effect on yield. Similar inconsistencies in yield among years and crop cultivars near wildflower strips were recorded in tomatoes (Balzan et al. 2016).

In conclusion, cucumber fields contain a diverse community of beneficial insects that require pollen and nectar for their survival, and these populations can be manipulated by adding floral resources, such as buckwheat and mustard, to cucumber fields. Effects on yield in our study were limited; some important factors that could be underlying the lack of positive effect of flowers on the number of beneficial insects in the crop field in our experiments are the size of the flower strips we used in relation to the field or landscape, the ephemeral nature of the flower strips, and the type and combination of flowers chosen for the strips. Bees and other highly mobile insects, such as ladybeetles, have demonstrated sensitivities to the quality of the landscape as a whole, meaning that local-scale management may be insufficient support for their populations (Shackelford et al. 2013, Petersen and Nault 2014, Kremen and M'Gonigle 2015, Park et al. 2015, Rusch et al. 2016). Generally, larger areas of floral resources support greater beneficial insect abundance and diversity (Blaauw and Isaacs 2012). Relative to the entire field, the total area of the flower strips in our study was small in both years, comprising <0.001% of the total area of the cucumber field. Increasing the size of the within-field floral areas may improve the total number of beneficial insects dispersing into cropped areas of the field. It is also possible that the effects of habitat management may be weaker in temperate regions, such as the

Midwestern United States, compared with arid or semiarid landscapes that have fewer overall resources (Brooker et al. 2014). Perennial insectary plantings are thought to improve natural enemy diversity and abundance by increasing the carrying capacity of the area over time (Landis et al. 2000, Blaauw and Isaacs 2014, Iverson et al. 2014). However, cucumbers are rotated annual crops, making the improvement of the beneficial insect community with perennial plants a challenge. Long-lasting floral resources can be provided through farmscaping, where permanent flower plantings are established on nonproduction land within the farm (Smukler et al. 2010). This could work well in smaller farms where distances of rotated annual crops to the permanent flower resource do not exceed 100 m (Kohler et al. 2008, Morandin and Kremen 2013). Unfortunately, in most of the commercial vegetable production systems in the North Central United States, crop rotation distances exceed well beyond this range. A third consideration is that we used single species in the flower strips that may not have delivered the best resources for the needs of the beneficials found in the cucumber system. Flower strips can be designed with flower mixes or specific flowers that are tailored for enhancing particular species of beneficial insects (Haaland et al. 2011; Balzan et al. 2014, 2016). While we selected plants in the current study that flowered concurrently with the cucumbers, future research should explore flowering species that may attract pollinators and natural enemies to fields prior to cucumber bloom.

As has been concluded by other studies (Shackelford et al. 2013, Iverson et al. 2014, Morandin et al. 2014, Duru et al. 2015), the responses of natural enemies and pollinators to the addition of floral resources proved to be similar, meaning that their management is compatible. Planting buckwheat and mustard in larger patches in nonproduction areas of the field such as the driveways and field margins may improve effects on beneficial insects at the local scale (Blaauw and Isaacs 2012, Morandin et al. 2014). While increasing the total area of resources has the potential to benefit natural enemies, pollinators, and yield, the question remains of whether or not benefits of increased habitat management would outweigh grower costs required for optimal implementation (van Lenteren 2012, McCarthy et al. 2012, Kleijn et al. 2015). However, in low-input settings, such as small, organic farms that are not as intensively managed, improvements to the habitat on the arthropod community may become more apparent. Floral provisioning has been employed in other agroecosystems with some success (Haaland et al. 2011, Walton and Isaacs 2011, Brennan 2013, Garibaldi et al. 2014, Nayak et al. 2015). The most important factor in determining ecosystem services and beneficial insect abundance at the local scale may be the quality of the landscape as a whole (Rusch et al. 2016). Habitat management for beneficial insects still holds tremendous potential to improve insect conservation and sustainability, but many questions remain before its application in cucurbit agroecosystems can move to widespread implementation.

Acknowledgments

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References Cited

- Artz, D. R., and B. A. Nault. 2011. Performance of *Apis mellifera*, *Bombus impatiens*, and *Peponapis pruinosa* (Hymenoptera: Apidae) as pollinators of pumpkin. *J. Econ. Entomol.* 104: 1153–1161.
- Ascher, J. S., and J. Pickering. 2016. Discover Life bee species guide and world checklist (Hymenoptera: Apoidea: Anthophila). (http://www.discoverlife.org/mp/20q?guide=Apoidea_species, accessed 21 December 2016).
- Balzan, M. V., G. Bocci, and A. C. Moonen. 2014. Augmenting flower trait diversity in wildflower strips to optimize the conservation of arthropod functional groups for multiple agroecosystem services. *J. Insect Cons.* 18: 713–728.
- Balzan, M. V., G. Bocci, and A. C. Moonen. 2016. Utilisation of plant functional diversity in wild flower strips for the delivery of multiple agroecosystem services. *Entomol. Exp. Appl.* 158: 304–319.
- Batáry, P., L. V. Dicks, D. Kleijn, and W. J. Sutherland. 2015. The role of agri-environment schemes in conservation and environmental management. *Cons. Biol.* 29: 1006–1016.
- Benjamin, F. E., J. R. Reilly, and R. Winfree. 2014. Pollinator body size mediates the scale at which land use drives crop pollination services. *J. Appl. Ecol.* 51: 440–449.
- Berndt, L. A., and S. D. Wratten. 2005. Effects of alyssum flowers on the longevity, fecundity, and sex ratio of the leafroller parasitoid *Dolichogenidea tasmanica*. *Biol. Control* 32: 65–69.
- Bhardwaj, R. K., and S. Kumar. 2014. Studies on correlation between yield and seed characters in cucumber, *Cucumis sativus* L. *Intern. J. Farm Sci.* 2: 54–58.
- Blaauw, B. R., and R. Isaacs. 2012. Larger wildflower plantings increase natural enemy density, diversity, and biological control of sentinel prey, without increasing herbivore density. *Ecol. Entomol.* 37: 386–394.
- Blaauw, B. R., and R. Isaacs. 2014. Flower plantings increase wild bee abundance and the pollination services provided to a pollination-dependent crop. *J. Appl. Ecol.* 51: 890–898.
- Brennan, E. B. 2013. Agronomic aspects of strip intercropping lettuce with alyssum for biological control of aphids. *Biol. Control* 65: 302–311.
- Carmona D.M., and D.A. Landis. 1999. Influence of refuge habitats and cover crops on seasonal activity-density of ground beetles (Coleoptera: Carabidae) in field crops. *Environmental Entomology*. 28(6): pp.1145–1153.
- Carvell, C., D. B. Roy, S. M. Smart, R. F. Pywell, C. D. Preston, and D. Goulson. 2006. Declines in forage availability for bumblebees at a national scale. *Biol. Conserv.* 132: 481–489.
- Chaplin-Kramer, R., M. E. O'Rourke, E. J. Blitzer, and C. Kremen. 2011. A meta-analysis of crop pest and natural enemy response to landscape complexity. *Ecol. Lett.* 14: 922–932.
- Cook, S. M., C. S. Awmack, D. A. Murray, and I. H. Williams. 2003. Are honey bees' foraging preferences affected by pollen amino acid composition? *Ecol. Entomol.* 28: 622–627.
- Costello, M. J., and M. A. Altieri. 1995. Abundance, growth-rate and parasitism of *Brevicoryne brassicae* and *Myzus persicae* (Homoptera: Aphididae) on broccoli grown in living mulches. *Agric. Ecosyst. Environ.* 52: 187–196.
- Danner, N., S. Härtel, and I. Steffan-Dewenter. 2014. Maize pollen foraging by honey bees in relation to crop area and landscape context. *Basic Appl. Ecol.* 15: 677–684.
- Desneux, N., A. Decourtye, and J. Delpuech. 2007. The sublethal effects of pesticides on beneficial arthropods. *Ann. Rev. Entomol.* 52: 81–106.
- Duru, M., O. Therond, G. Martin, R. Martin-Clouaire, M. Magne, E. Justes, E. Journet, J. Aubertot, S. Sarvary, J. Bergez, et al. 2015. How to implement biodiversity-based agriculture to enhance ecosystem services: A review. *Agron. Sustain. Dev.* 35: 1259–1281.
- Fiedler, A. K., D. A. Landis, and S. D. Wratten. 2008. Maximizing ecosystem services from conservation biological control: The role of habitat management. *Biol. Control* 45: 254–271.
- Gajc-Wolska, J., K. Kowalczyk, J. Mikas, and R. Drajski. 2011. Efficiency of cucumber (*Cucumis sativus* L.) pollination by bumblebees (*Bombus terrestris*). *Acta Scientiarum Polonorum Hortorum Cult.* 10: 159–169.
- Garibaldi, L. A., I. Steffan-Dewenter, R. Winfree, M. A. Aizen, R. Bommarco, S. A. Cunningham, C. Kremen, L. G. Carvalheiro, L. D. Harder, O. Afik,

- et al. 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. *Science* 339: 1608–1611.
- Garibaldi, L. A., L. G. Carvalheiro, S. D. Leonhardt, M. A. Aizen, B. R. Blaauw, R. Isaacs, M. Kuhlmann, D. Kleijn, A. M. Klein, C. Kremen, et al. 2014. From research to action: Enhancing crop yield through wild pollinators. *Front. Ecol. Environ.* 12: 439–447.
- Giannini, T. C., L. A. Garibaldi, A. L. Acosta, J. S. Silva, K. P. Maia, A. M. Saraiva, P. R. Guimarães, and A.M.P. Kleinert. 2015. Native and non-native supergeneralist bee species have different effects on plant-bee networks. *PLoS ONE*. 10: e0137198.
- Goulson, D., E. Nicholls, C. Botias, and E. L. Rotheray. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science* 347: 16–11.
- Goverde, M., K. Schweizer, B. Baur, and A. Erhardt. 2002. Small-scale habitat fragmentation effects on pollinator behaviour: Experimental evidence from the bumblebee *Bombus veteranus* on calcareous grasslands. *Biol. Conserv.* 104: 293–299.
- Grant, V. 1950. Flower constancy of bees. *Bot. Rev.* 16: 379–398.
- Greenleaf, S. S., and C. Kremen. 2006. Wild bee species increase tomato production and respond differently to surrounding land use in Northern California. *Biol. Conserv.* 133: 81–87.
- Greenleaf, S. S., N. M. Williams, R. Winfree, and C. Kremen. 2007. Bee foraging ranges and their relationship to body size. *Oecologia* 153: 589–596.
- Haaland, C., R. E. Naisbit, and L. Bersier. 2011. Sown wildflower strips for insect conservation: A review. *Insect Conserv. Divers.* 4: 60–80.
- Hinds, J., and C.R.R. Hooks. 2013. Population dynamics of arthropods in a sunn-hemp zucchini interplanting system. *Crop Prot.* 53: 6–12.
- Holzschuh, A., J. H. Dudenhöffer, and T. Tscharntke. 2012. Landscapes with wild bee habitats enhance pollination, fruit set and yield of sweet cherry. *Biol. Conserv.* 153: 101–107.
- Hooks, C.R.R., H. R. Valenzuela, and J. Defrank. 1998. Incidence of pests and arthropod natural enemies in zucchini grown with living mulches. *Agric. Ecosyst. Environ.* 69: 217–231.
- Ismail, S. M., and K. Ozawa. 2007. Improvement of crop yield, soil moisture distribution and water use efficiency in sandy soils by clay application. *Appl. Clay Sci.* 37: 81–89.
- Iverson, A. L., L. E. Marin, K. K. Ennis, D. J. Gonthier, B. T. Connor-Barrie, J. L. Remfert, B. J. Cardinale, and I. Perfecto. 2014. Do polycultures promote win-wins or trade-offs in agricultural ecosystem services? A meta-analysis. *J. Appl. Ecol.* 51: 1593–1602.
- Julier, H. E., and T. H. Roulston. 2009. Wild bee abundance and pollination service in cultivated pumpkins: Farm management, nesting behavior and landscape effects. *J. Econ. Entomol.* 102: 563–573.
- Kennedy, C. M., E. Lendorf, M. C. Neel, N. M. Williams, T. H. Ricketts, R. Winfree, R. Bommarco, C. Brittain, A. L. Burley, D. Cariveau, et al. 2013. A global quantitative synthesis of local and landscape effects on wild bee pollinators in agroecosystems. *Ecol. Lett.* 16: 584–599.
- Kleijn, D., R. Winfree, I. Bartomeus, L. G. Carvalheiro, M. Henry, R. Isaacs, A. M. Klein, C. Kremen, L. K. M'Gonigle, R. Rader, et al. 2015. Delivery of crop pollination services is an insufficient argument for wild pollinator conservation. *Nat. Comm.* 6: 7414.
- Kleijn, M., B. E. Vaissiere, J. H. Cane, I. Steffan-Dewenter, S. A. Cunningham, C. Kremen, and T. Tscharntke. 2007. Importance of pollinators in changing landscapes for world crops. *Proc. R Soc. B.* 274: 303–313.
- Kohler, F., J. Verhulst, R. Van Klink, and D. Kleijn. 2008. At what spatial scale do high-quality habitats enhance the diversity of forbs and pollinators in intensively farmed landscapes?. *Journal of Applied Ecology*. 45(3): pp.753–762.
- Kremen, C., and A. Miles. 2012. Ecosystem services in biologically diversified versus conventional farming systems: Benefits, externalities, and trade-offs. *Ecol. Soc.* 17: 40.
- Kremen, C., and L. K. M'Gonigle. 2015. Small-scale restoration in intensive agricultural landscapes supports more specialized and less mobile pollinator species. *J. Appl. Ecol.* 52: 602–610.
- Landis, D. A., S. D. Wratten, and G. M. Gurr. 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Ann. Rev. Entomol.* 45: 175–201.
- Langellotto, G. A., and R. F. Denno. 2004. Responses of invertebrate natural enemies to complex-structured habitats: A meta-analytical synthesis. *Oecologia* 139: 1–10.
- Letourneau, D. K., I. Armbrecht, B. S. Rivera, J. M. Lerma, E. J. Carmona, et al. 2011. Does plant diversity benefit agroecosystems? A synthetic review. *Ecol. Appl.* 21: 9–21.
- Londsdorf, E., C. Kremen, T. Ricketts, R. Winfree, N. Williams, and S. Greenleaf. 2009. Modeling pollination services across agricultural landscapes. *Ann. Bot.* 103: 1589–1600.
- Lowenstein, D. M., A. S. Huseuth, and R. L. Groves. 2012. Response of wild bees (Hymenoptera: Apoidea: Anthophila) to surrounding land cover in Wisconsin pickling cucumber. *Environ. Entomol.* 41: 532–540.
- McCarthy, D. P., P. F. Donald, J.P.W. Scharlemann, G. M. Buchanan, A. J. Balmford, J. M. Green, L. A. Bennun, N. D. Burgess, L. D. Fishpool, S. T. Garnett, et al. 2012. Financial costs of meeting global biodiversity conservation targets: Current spending and unmet needs. *Science* 338: 946–949.
- McGregor, S. E. 1976. Insect pollination of cultivated crops. U.S. D. A., Agric. Res. Serv. Agric. Handbook 496, Washington, D.C.
- Mitchell, T.B. (1960) Bees of the eastern United States. I. Technical bulletin (North Carolina Agricultural Experiment Station). 141: 1–538.
- Mitchell, T.B. (1962) Bees of the eastern United States. II. Technical bulletin (North Carolina Agricultural Experiment Station). 152: 1–557.
- Morandin, L. A., and C. Kremen. 2013. Hedgerow restoration promotes pollinator populations and exports native bees to adjacent fields. *Ecol. Appl.* 23: 829–839.
- Morandin, L. A., R. F. Long, and C. Kremen. 2014. Hedgerows enhance beneficial insects on adjacent tomato fields in an intensive agricultural landscape. *Agric. Ecosyst. Environ.* 189: 164–170.
- Motzke, I., T. Tscharntke, T. C. Wagner, and A. Klein. 2015. Pollination mitigates cucumber yield gaps more than pesticide and fertilizer use in tropical smallholder gardens. *J. Appl. Ecol.* 52: 261–269.
- Nayak, G. K., S.P.M. Roberts, M. Garratt, T. D. Breeze, T. Tscheulin, J. Harrison-Cripps, I. N. Vogitzakis, M. T. Stride, and S. G. Potts. 2015. Interactive effect of floral abundance and semi-natural habitats on pollinators in field beans (*Vicia faba*). *Agric. Ecosyst. Environ.* 199: 58–66.
- Nicholls, C. I., and M. A. Altieri. 2013. Plant biodiversity enhances bees and other insect pollinators in agroecosystems. A review. *Agron. Sustain. Develop.* 33: 257–274.
- Norfolk, O., M. P. Eichhorn, and F. S. Gilbert. 2015. Contrasting patterns of turnover between plants, pollinators and their interactions. *Divers. Distrib.* 21: 405–415.
- Park, M. G., E. J. Blitzer, J. Gibbs, J. E. Losey, and B. N. Danforth. 2015. Negative effects of pesticides on wild bee communities can be buffered by landscape context. *Proc. R. Soc. B.* 282: e1342.
- Peng, Y. B., Y. Li, Y. Hao, Z. Xu, and S. Bai. 2004. Nectar production and transportation in the nectaries of the female *Cucumis sativus* L. flower during anthesis. *Protoplasma* 22: 71–78.
- Pereira, A.L.C., T. C. Taques, J.O.S. Valim, A. P. Madureira, and W. G. Campos. 2015. The management of bee communities by intercropping with flowering basil (*Ocimum basilicum*) enhances pollination and yield of bell pepper (*Capsicum annuum*). *J. Insect Conserv.* 19: 479–486.
- Petersen, J. D., and B. A. Nault. 2014. Landscape diversity moderates the effects of bee visitation frequency to flowers on crop production. *J. Appl. Ecol.* 51: 1347–1356.
- Petersen, J. D., S. Reiners, and B. A. Nault. 2013. Pollination services provided by bees in pumpkin fields supplemented with either *Apis mellifera* or *Bombus impatiens* or not supplemented. *PLoS ONE* 8: e69819.
- Phillips, B. W., and M. M. Gardiner. 2016. Does local habitat management or large-scale landscape composition alter the biocontrol services provided to pumpkin agroecosystems? *Biol. Control* 92: 181–194.
- Platt, J. O., J. S. Caldwell, and L. T. Kok. 1999. Effect of buckwheat as a flowering border on populations of cucumber beetles and their natural enemies in cucumber and squash. *Crop Prot.* 18: 305–313.
- Rahil, M. H., and M. Qanadillo. 2015. Effects of different irrigation regimes on yield and water use efficiency of cucumber crop. *Agric. Water Manag.* 148: 10–15.

- Rebek, E. J., C. S. Sadof, and L. M. Hanks. 2005. Manipulating the abundance of natural enemies in ornamental landscapes with floral resource plants. *Biol. Control* 33: 203–216.
- Riedinger, V., M. Renner, M. Rundlof, I. Steffan-Dewenter, and M. Holzschuh. 2014. Early mass-flowering crops mitigate pollinator dilution in late-flowering crops. *Landsc. Ecol.* 29: 425–435.
- Root, R. B. 1973. Organization of a plant-arthropod association in simple and diverse habitats: The fauna of collards (*Brassica oleracea*). *Ecol. Monog.* 43: 95–124.
- Roulston, T. H., and K. Goodell. 2011. The role of resources and risks in regulating wild bee populations. *Ann. Rev. Entomol.* 56: 293–312.
- Rusch, A., R. Chaplin-Kramer, M. Gardiner, V. Hawro, J. Holland, D. Landish, C. Thies, T. Tscharntke, W. W. Weisser, C. Winqvist, et al. 2016. Agricultural landscape simplification reduces natural pest control: A quantitative synthesis. *Agric. Ecosyst. Environ.* 221: 198–204.
- Shackelford, G., P. R. Steward, T. G. Benton, W. E. Kunin, S. G. Potts, J. C. Biesmeijer, and S. M. Sait. 2013. Comparison of pollinators and natural enemies: A meta-analysis of landscape and local effects on abundance and richness in crops. *Biol. Rev.* 88: 1002–1021.
- Shuler, R. E., T. H. Roulston, and G. E. Farris. 2005. Farming practices influence wild pollinator populations on squash and pumpkin. *J. Econ. Entomol.* 98: 790–795.
- Smith, A. A., M. Bentley, and H. L. Reynolds. 2013. Wild bees visiting cucumber on Midwestern U.S. organic farms benefit from near-farm semi-natural areas. *J. Econ. Entomol.* 106: 97–106.
- Smukler, S.M., S. Sánchez-Moreno, S.J. Fonte, H. Ferris, K. Klonsky, A.T. O'geen, K.M. Scow, K.L. Steenwerth, and L.E. Jackson. 2010. Biodiversity and multiple ecosystem functions in an organic farmscape. *Agriculture, ecosystems & environment*. 139(1): pp.80–97.
- Snyder, W. E., and D. H. Wise. 2008. Contrasting trophic cascades generated by a community of generalist predators. *Ecology* 82: 1571–1583.
- Stanghellini, M. S., J. T. Ambrose, and J. R. Schultheis. 1997. The effects of honey bee and bumblebee pollination on fruit set and abortion of cucumber and watermelon. *Am. Bee J.* 137: 386–391.
- van Lenteren, J. C. 2012. The state of commercial augmentative biological control: Plenty of natural enemies, but a frustrating lack of uptake. *BioControl* 57: 1–20.
- Walton, N. J., and R. Isaacs. 2011. Influence of native flowering plant strips on natural enemies and herbivores in adjacent blueberry fields. *Environ. Entomol.* 40: 697–705.
- Wanner, H., H. Gu, and S. Dorn. 2006. Nutritional value of floral nectar sources for flight in the parasitoid wasp, *Cotesia glomerata*. *Physiol. Entomol.* 31: 127–133.
- Williams, N. M., E. E. Crone, T. Roulston, R. L. Minckley, L. Packer, and S. G. Potts. 2010. Ecological and life-history traits predict bee species responses to environmental disturbances. *Biol. Conserv.* 143: 2280–2291.
- Winfree, R., I. Bartomeus, and D. P. Cariveau. 2011. Native pollinators in anthropogenic habitats. *Ann. Rev. Ecol. Evol. Syst.* 42: 1–22.
- Winfree, R., J. W. Fox, N. M. Williams, J. R. Reilly, and D. P. Cariveau. 2015. Abundance of common species, not species richness, drives delivery of a real-world ecosystem service. *Ecol. Lett.* 18: 626–635.
- Woodcock, B. A., J. Savage, J. M. Bullock, M. Nowakowski, J.R.B. Tallowin, and R. F. Pywell. 2014. Enhancing floral resources for pollinators in productive agricultural grasslands. *Biol. Conserv.* 171: 44–51.