




Herbivores and natural enemies of brassica crops in urban agriculture

David M. Lowenstein^{1,2}  · Emily S. Minor^{2,3}

© Springer Science+Business Media, LLC, part of Springer Nature 2018

Abstract

Urban agriculture has been growing in popularity around the globe. As more land is allocated to urban agriculture, there is a greater need to understand arthropod herbivores and natural enemies in these sites. The area and production type of urban agriculture could influence the risk of pest outbreaks, since larger food production areas are hypothesized to host more abundant herbivore populations. To determine the potential for pest outbreaks, we sampled for pests and above-ground natural enemies at three types of sites with variable amounts of cultivated areas: residential gardens, community gardens, and urban farms. We focused on pests of brassica, a widely cultivated crop family attacked by cabbageworms and aphids. We investigated the relationships of garden characteristics and surrounding land cover on natural enemies and herbivores of brassica. More herbivores and plant damage were expected in larger community gardens and urban farms. However, herbivore populations were low across sites and not explained by garden characteristics or area of production. Herbivory on brassica averaged less than 15% at all sites. Limited plant damage and low herbivore numbers may be attributed to the positive effects of garden flowers on parasitoids and high numbers of parasitoids and generalist predators across sites. Garden area and floral resources had positive relationships with natural enemy abundance, although community composition was similar across sites. Since arthropod natural enemies were abundant across all types of food production, this suggests that urban agriculture is a beneficial habitat that could support regulating ecosystem services such as biological control.

Keywords Aphid · Cabbageworm · Parasitoid · Resource concentration hypothesis

Introduction

Urban agriculture has been growing in popularity over the last several decades (Mok et al. 2014; Tornaghi 2014). Food production in the city provides economic and public health benefits, including employment in low-income neighborhoods (Grewal

and Grewal 2012) and alleviating food insecurity in some communities (Fuller et al. 2007; Zezza and Tasciotti 2010). However, the success of urban agriculture depends at least partially on the surrounding ecosystem, as most food production is tightly linked with arthropod-mediated ecosystem services including pollination and pest management (Lin et al. 2015). Therefore, to increase productivity and sustainability of urban agriculture, we must increase our understanding of urban ecosystems.

Insect pest damage is one of the most common challenges cited by urban gardeners (Gregory et al. 2016). Since many gardens follow organic practices, pest management by arthropod natural enemies (i.e., biological control) is a key component at minimizing crop damage. Studies in urban agriculture reveal 50% or greater predation or parasitism rates on sentinel prey items, confirming the value of pest suppression services provided by natural enemies (Gardiner et al. 2014; Philpott and Bichier 2017; Lowenstein et al. 2017). Research has shown that natural enemy communities in cities are affected by local variables such as garden area, mulch cover, and flowering plant diversity (Bennett and Gratton 2012; Otoshi et al. 2015; Burks and Philpott 2017). Characteristics of the

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s11252-018-0738-x>) contains supplementary material, which is available to authorized users.

✉ David M. Lowenstein
dmaxlow@gmail.com

Emily S. Minor
eminor@uic.edu

¹ Present address: Department of Horticulture, Oregon State University, 2750 SW Campus Way, Corvallis, OR 97331, USA

² Department of Biological Sciences, University of Illinois at Chicago, 845 W. Taylor Street (M/C 066), Chicago, IL 60607, USA

³ Institute for Environmental Science and Policy, University of Illinois at Chicago, Chicago, IL, USA

surrounding landscape may be important too (Burkman and Gardiner 2014; Egerer et al. 2016), although some studies show that local factors have a greater influence on natural enemies (e.g., Bennett and Gratton 2012; Philpott et al. 2014).

While herbivorous arthropods have been linked with plant abundance, diversity, and structure in a variety of other urban green spaces (Shrewsbury and Raupp 2006; Mata et al. 2017; Philpott et al. 2014), very few studies have examined crop pests in urban agriculture. A recent study of community gardens in New York City (USA) found that peak populations of some crop pests greatly exceeded “action thresholds” (the point at which pest control action should be taken) in >90% of gardens (Gregory et al. 2016). Therefore, urban agriculture provides an important and novel setting to examine the relationships among herbivores, plant production areas, and natural enemies.

Herbivores with restricted host ranges are hypothesized to have larger populations in larger host-plant patches (Root 1973). This resource concentration hypothesis, a bottom-up force of insect regulation, has been studied extensively. However, the results demonstrate conflicting outcomes, with some studies finding a positive relationship between insect pests and patch area (Kareiva 1985; Bach 1988) and other studies finding negative or neutral effects (Cromartie 1975; Capman et al. 1990; Grez and Gonzalez 1995). Variability in the relationship between pests and patch size has been explained by distance between patches (Capman et al. 1990) and organism-dependent dispersal behavior (Grez and Gonzalez 1995; Hamback and Englund 2005). While the bottom-up approach is a useful framework for understanding pest population patterns, top-down controls by arthropod predators (Walker and Jones 2001; Denno et al. 2002; Costamagna and Landis 2006) are alternate, if not synergistic, explanations for herbivore dynamics.

Agricultural sites with resource patches of different sizes could structure herbivore and natural enemy populations in different ways. Three North American types of urban agriculture provide useful contrasts for evaluating the resource concentration hypothesis and potential risk for herbivory. First, urban farms focus on commercial sale of crops grown outdoors, in greenhouses, or on rooftops. This food production type represents the largest total area and size of individual resource patches. Second, community gardens are usually allotment-type gardens (Lin et al. 2015) where food is typically grown in polycultures for personal consumption or commercial sale. Unlike urban farms, which are managed as a single unit, individual plots are managed independently in most community gardens. Finally, residential gardens, or “home-food gardens”, are found at multi- or single-family homes where plants are grown exclusively for personal

consumption (Taylor and Lovell 2014). In our study area, single-family residential lots are typically standardized at 290 or 464 m² (Chicago Zoning Ordinance 17–2-0303), and home gardens have mean crop production areas of 12–23 m² (Taylor et al. 2016). This is in contrast to community gardens, which typically cover at least an entire residential lot, and urban farms, which often comprise multiple lots. Consequently, residential gardens have the smallest cultivated areas, and therefore resource patches, compared to farms and community gardens.

In this study, we examined pests and natural enemies across three food production types in Chicago, IL (USA). We focused on crops in the brassica family, which are common in urban agriculture and include plants such as cabbage, kale, and broccoli. Brassica plants have a closely evolved pest complex that includes specialized aphids and cabbageworms (Bonnemaïson 1965). Our goal was to characterize these pests and their relationships with local garden characteristics and above-ground predators and parasitoids. Specifically, we investigated if there was support for the resource concentration hypothesis on brassica in the urban setting, using garden area and number of brassica patches as proxies for resource concentration. We expected that urban farm sites—the largest of the three food production types—would have the highest amount of brassica herbivores and also natural enemies. We also evaluated how additional characteristics within and around gardens, such as herbaceous cover and floral diversity, influence herbivores, predators, and parasitoids in brassica. This work provides foundational data on insects in urban agriculture while building on theoretical information that identifies drivers of herbivore populations.

Methods

Study sites

All study sites were in Chicago, IL (USA), except for one urban farm in the adjacent suburb of Evanston, IL. The climate of Chicago is classified as humid continental, with mean monthly temperatures during the summer (June–August) ranging from 21–23 Celsius and mean monthly precipitation during the summer ranging from 8.8–12.4 cm (Illinois State Water Survey).

We located all sites through posting in a local urban agricultural policy listserv and selected sites across different urban neighborhoods with a mean minimum distance between nearest sites of 1.9 km (range 0.72–4.2 km). We included 29 sites from three types of agricultural production: residential gardens ($N=12$), community gardens ($N=9$), and urban farms ($N=8$). This study design allowed us to assess a broad range of resource patch sizes (Table 1). Community gardens and urban farms were included if at least 20 brassica plants

Table 1 Food and garden attributes of each type of urban agriculture

	Urban farm	Community garden	Residential garden
Mean number of brassica rows (\pm SE)	8.1 \pm 1.9	13.9 \pm 4.5	1.4 \pm 0.18
Mean garden area (\pm SE) m ²	2088 \pm 611	266 \pm 71	22.3 \pm 3
N sample sites	8	9	12

(range 20–200+) were cultivated. Since these cultivated areas were not always planted in uniform patterns (i.e. plant rows of equal length), it was not always possible to sample plants and inspect for arthropods in a linear row. Rows of cultivated brassica were typically 3–4 m in length, except for a single residential site with only 5 cultivated brassica plants in a row that was approximately 2.5 m in length. Farms were nearly 8 \times larger than the other types of agriculture, but all sites grew multiple crops and irrigated plants regularly. On average, brassica crops covered 42% of cultivated areas, with cabbage and kale as the most common cultivars. At each site, we measured the number of cultivated areas with brassica crops (“brassica rows”). We also calculated the total area of planted crops, flowers, and tilled soil (“garden area”).

We queried gardeners on their growing practices, but their response rate to our survey was below 50%. Of responding community gardens ($N=9$) and farms ($N=4$), all but one followed organic practices, and every community garden prohibited insecticide application. A previous study of residential garden management indicated that 20% ($N=6/30$) of homeowners applied insecticides to their garden at least once a year (Lowenstein et al. 2015), so we assume that a similarly low number of homeowners applied insecticides to the residential gardens in this study.

Sampling for insect pests

We focused on two important groups of brassica pests. The first group, cabbageworms, includes a complex of 3 specialist herbivore species: *Trichoplusia ni* (cabbage looper), *Plutella xylostella* (diamondback moth), and *Pieris rapae* (imported cabbageworm). Cabbageworm eggs and larvae are commonly parasitized by specialist parasitic wasps (Godin and Boivin 1998; Shelton et al. 2002), but records exist of predation by lacewings, yellow jackets, and other arthropods (Richards 1940; Schmaedick and Shelton 1999; Lowenstein et al. 2017). The second group includes sap-feeding aphids, primarily *Myzus persicae* (green peach aphid) and *Brevicoryne brassicae* (cabbage aphid), which are attacked by a broader range of specialist and generalist predators (White et al. 1995; Snyder, and , Snyder G.B., Finke D.L., Straub C.S. 2006).

We sampled for cabbageworms and aphids at six time intervals between 16 June and 26 August 2014, counting pests and estimating defoliation every other week. At each site, we randomly selected five *Brassica oleracea* plants (e.g., cabbage, broccoli, kale) and inspected five leaves on each plant

for the presence of aphids and cabbageworm eggs, larvae, and pupae. In the case of compact head cabbages, we inspected the entire visible part of the plant, including the wrapper leaves, instead of pulling off individual leaves. In addition to counting pests, we estimated defoliation on the five selected plants on a 0–100% scale at 10% intervals. As we walked through crop rows with brassica, we also recorded the presence of adult cabbageworms in-flight. Cabbageworms were identified to the species level but aphids were not. At one residential site, brassica plants grew poorly. Therefore, we excluded this site from analysis of pest populations, resulting in 28 sample sites for pests.

Sampling for natural enemies

We set up four 18 \times 14 cm yellow sticky cards (Alpha Scents: West Linn, OR) within brassica crops at each farm or garden. Cards remained in the field for two-week intervals and were replaced when we visited sites to record pests. In total, we had 5 two-week intervals of natural enemy sampling with sticky cards placed on 16 June, 28 June, 14 July, 28 July, and 11 August 2014. After each sampling period, we brought yellow sticky cards to the lab to identify predators and parasitoids on each card. We identified parasitoid wasps to the family level using Goulet and Huber (1993). We also noted parasitoids in the Aphidiinae subfamily of Braconidae, which are specialist parasitoids of several aphid species. From here on, we refer to this subfamily as ‘specialist parasitoids.’ Additionally, we recorded the abundance of common insect predators that may attack aphids and the immature life stages of cabbageworms. These predators, collected on sticky cards, included lady beetles (Coleoptera: Coccinellidae), minute pirate bugs (Hemiptera: Anthocoridae), predatory wasps (Hymenoptera: Vespidae, Crabronidae), hover flies (Diptera: Syrphidae), long-legged flies (Diptera: Dolichopodidae), and lacewings (Neuroptera). From the parasitoid and insect predator families listed above, we calculated the Shannon diversity index of natural enemies for each site.

Environmental variables

In each site, we measured floral richness and abundance as potential explanatory variables. Floral abundance and richness were measured by counting the number of flowering plant units and species on 13 July and 1 August within the entire site. Floral richness and abundance were averaged over both

dates for all analyses. Since adult cabbageworms are mobile, we also measured two landscape variables around each garden: the percent of grass and the percent of canopy cover within 1000 m of sites. Impervious surface was not included, since it was significantly correlated with grass cover ($r = -0.46$). Land cover data were obtained from a classified high-resolution (submeter) Quikbird satellite image and the Tabulate Area tool in ArcGIS 9.3.

Data analysis

First, we collected information about the phenology of natural enemies, herbivores, and herbivory across the growing season, comparing populations of each insect group between dates and food production types using two-way ANOVAs. Next, we used a model selection framework to identify the variables that best predicted herbivore and natural enemy populations.

Herbivore model selection

We used multiple regression to examine how site characteristics and natural enemy populations affected four response variables: (1) abundance of cabbageworm adults, (2) abundance of cabbageworm larvae, (3) abundance of aphids, and (4) defoliation. Response variables were pooled across sampling dates and food production types for these analyses. Local variables in sites included garden area (m^2), floral richness, floral abundance, and number of brassica rows. Garden area was log-transformed to improve normality. Landscape variables included the percent of grass and canopy cover within 1000 m of sites. Natural enemy measurements included abundance of all natural enemies, abundance of parasitoids, abundance of predators, and Shannon diversity of natural enemy taxa pooled across dates of sticky card sampling.

We used an inferential model-selection approach (MuMIn package) that considered model fit from all possible subsets of potential explanatory variables (R Development Core Team 2015; Barton 2015). We constrained the results of model selection by only considering models with $\Delta AICc < 2$. For each variable appearing in this subset of models, we calculated Akaike weights, as a relative measure of the likelihood of each model. Prior to model selection, we inspected variables for normality and models for multicollinearity using Variance Inflated Factors. Total natural enemy abundance was strongly correlated with parasitoid abundance ($r = 0.97$) and was removed from models.

Natural enemy model selection

A similar model selection approach was used to investigate the effects of local and landscape variables on total parasitoid and total predator abundance and each predator taxon

separately. Again, natural enemy data from each site was pooled across sample dates and food production types. As described above, total abundance of all natural enemies was highly correlated with parasitoid abundance so was not analyzed separately. Model selection for individual natural enemy taxa is presented in [Electronic Supplementary Material A](#). To investigate the relationship between natural enemy community composition and all herbivore life stages, we used a Redundancy analysis. Community composition was Hellinger-transformed, and we evaluated the percentage of constrained variation explained by an ordination of community composition against the four cabbageworm life stages and aphids. Finally, we evaluated if natural enemy community composition varied by type of food production using ANOSIM. All multivariate analyses were conducted with the vegan package (Oksanen et al. 2016).

Statement of data availability Upon acceptance, data will be submitted to an online repository.

Results

Garden characteristics

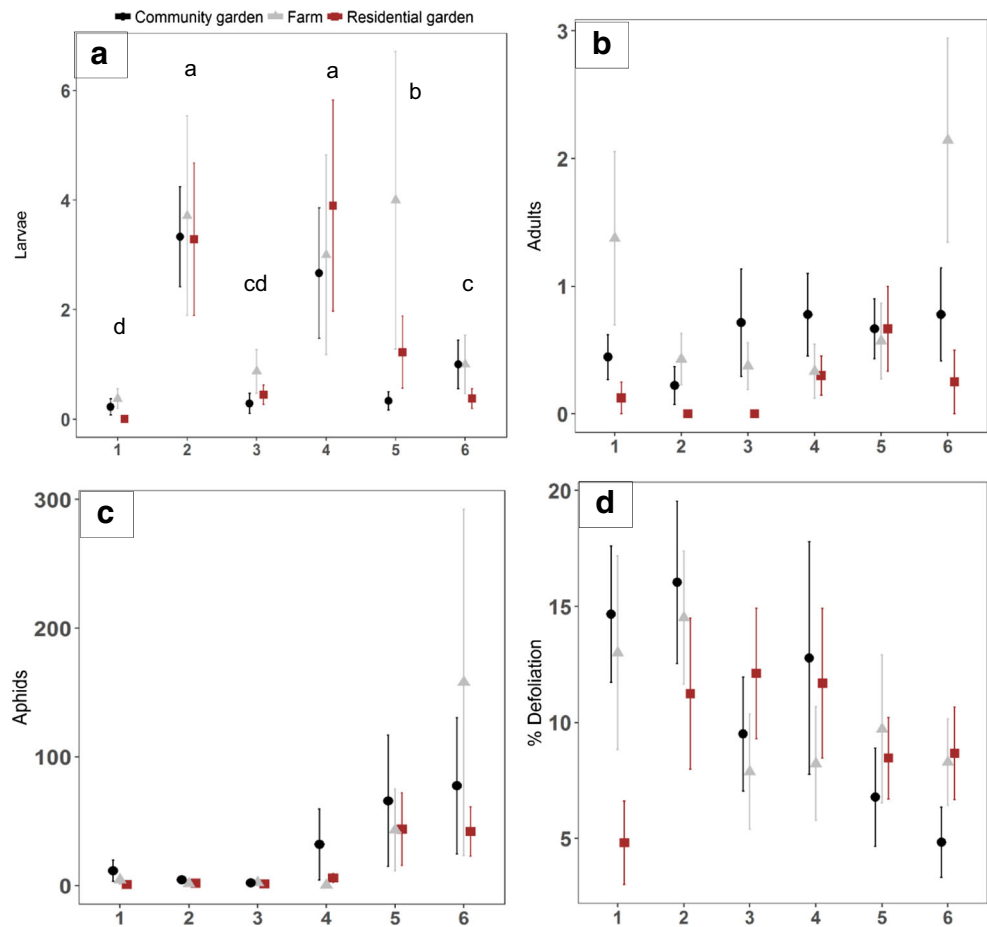
An average of 191 flowering plants (range 12–628) and 7 flowering species (range 1–13) were recorded in each site. Mean grass cover in a 1000 m buffer around sites was 18% (range 6–36%) and tree cover was 22% (range 2–69%). Sites had an average of 7 brassica rows (range: 1–41).

Herbivores in brassica

On average (\pm SE), 4.1 ± 0.6 eggs, 1.7 ± 0.3 larvae, and 0.3 ± 0.1 pupae of the three cabbageworm species were recorded during each visual scan of five brassica plants. Seventy-one percent of immature cabbageworms were *P. rapae*, and 28.5% the remaining immature cabbageworms were *T. ni*. Out of 102 adult cabbageworms observed, only 5 were *T. ni* or *X. plutella*. Consequently, most of our results on cabbageworms are applicable primarily to *P. rapae*. On average, 27.1 ± 8.2 aphids were recorded per brassica plant. Mean defoliation was $10.4 \pm 0.7\%$ of each leaf.

Immature cabbageworm ($F_{2, 143} = 1.48$, $P = 0.23$) and aphid abundance ($F_{2, 143} = 0.60$, $P = 0.55$) did not differ significantly between food production types. Sample date had a significant impact on pests with discrete population peaks of larvae in late June (sample period B) and again in late July or early August (sample periods D and E), and an increase in aphids after July 28 (Fig. 1). Mean aphid abundance was at least $2\times$ greater on August 11 and 26 than any previous sample date, but this was driven by a small number of sample locations and was not statistically significant.

Fig. 1 Mean cabbageworm larva (a), adult (b), and aphid (c) abundance per five plants, and defoliation (d), in three types of urban agriculture sites in Chicago, IL (USA). Each number on the X axis corresponds to a biweekly count: 1 = 16 June 2014, 2 = 30 June 2014, 3 = 14 July 2014, 4 = 28 July 2014, 5 = 11 August 2014, 6 = 26 August 2014. Lower-case letters in plots indicate significant differences between dates in larval abundance pooled across all sites



In general, the models for herbivores had little explanatory power. The explanatory model with the highest Akaike weights for cabbageworm eggs (Akaike weight = 0.71) and larvae (Akaike weight = 0.53) included only the intercept (Table 2). Other models with $\Delta\text{AICc} < 2$ for eggs and larvae included floral abundance, but neither variable was significant at $P < 0.05$. For adult cabbageworms, four models had $\Delta\text{AICc} < 2$. The most explanatory models included number of brassica rows in three models (Akaike weight = 0.78), and garden area in one model (Akaike weight = 0.18). While adult cabbageworms had a positive relationship with number of brassica beds (AIC = 127.7, $P = 0.01$), this pattern was not evident at the few sites with >15 brassica beds (Fig. 2a). Parasitoid abundance had the most explanatory effect on defoliation with a non-significant negative effect that appeared in 2 of 3 models (Table 2). The most explanatory model for aphid abundance only included the intercept, although number of Brassica rows was a significant variable in several models.

Natural enemies in brassica

Of natural enemies on yellow sticky cards, 72.7% were parasitoid wasps ($N = 20,550$), and 27.3% were insect predators ($N = 7720$). We identified parasitoids from 29 families;

Braconidae ($N = 7513$, 36.6% of parasitoids) and Ichneumonidae ($N = 4805$, 23.4% of parasitoids) were most abundant. Only two families were phytophagous, Cynipidae ($N = 73$, 0.4% of parasitoids) and Tanaostigmatidae ($N = 4$, 0.02% of parasitoids), but they were recorded infrequently. Of the insect predators recorded on sticky cards, long-legged flies ($N = 2526$, 32.7% of predators) and predatory wasps ($N = 2285$, 30% of predators) were the most abundant taxa (Electronic Supplementary Material B).

We found a significant effect of date on all parasitoids ($F_{4, 125} = 13.40$, $P < 0.001$), specialist aphid parasitoids ($F_{4, 125} = 4.06$, $P = 0.004$), and predators ($F_{4, 125} = 8.30$, $P < 0.001$) most of which were more abundant at later sampling dates (Fig. 3). Abundance of specific natural enemy taxa differed significantly across the growing season (Electronic Supplementary Material C). Food production type did not affect the abundance of parasitoids ($F_{2, 125} = 1.93$, $P = 0.15$), specialist aphid parasitoids ($F_{2, 125} = 1.67$, $P = 0.19$), or predators ($F_{2, 125} = 0.44$, $P = 0.64$).

The regression models for natural enemies had more explanatory power than the models for herbivores and suggested that local variables were the most important drivers of natural enemy abundance. Four of five models with $\Delta\text{AICc} < 2$ for parasitoids included garden area (Akaike weight = 0.86, Fig. 2b), while two included floral richness (Akaike weight = 0.36; Table 3).

Table 2 Summary of top-performing models that explain a portion of variation in herbivore abundance and have AICc <2

Herbivore	Model	Coefficients	AICc	Akaike weight	Maximum likelihood Pseudo R ²
Eggs	1. Intercept		229.3	0.71	
	2. Floral abundance	B = 0.0014	231.1	0.29	0.02
Larvae	1. Intercept		185.2	0.53	
	2. Floral abundance	B = 0.001	186.9	0.24	0.03
	3. Garden area	B = 0.117	186.9	0.23	0.02
Adults	1. # Brassica rows	B = 0.04*	127.7	0.42	0.11
	2. Intercept		129.1	0.22	
	3. # Predators + # Brassica rows	B1 = 0.01 B2 = 0.04*	129.5	0.18	0.14
	4. # Brassica rows + Garden area	B1 = 0.04* B2 = 0.09	128.5	0.18	0.14
Defoliation	1. Parasitoid abundance	B = -0.0009	201.4	0.54	0.11
	2. Parasitoid abundance + Floral richness	B = -0.0009 B = -0.04	203.1	0.23	0.16
	3. Intercept		203.1	0.23	
Aphids	1. Intercept		120.5	0.20	
	2. # Brassica rows	B = 0.02	120.6	0.20	0.07
	3. # Brassica rows + Parasitoid abundance	B1 = 0.02 B2 = -0.0006	120.6	0.19	0.14
	4. Parasitoid abundance	B = -0.0005	121.0	0.15	0.05
	5. Floral abundance + # Brassica rows	B1 = -0.001 B2 = 0.02*	121.9	0.09	0.10
	6. Floral richness + # Brassica rows	B1 = -0.04 B2 = 0.02*	122.0	0.09	0.10
	7. Floral abundance + # Brassica rows + Parasitoid abundance	B1 = -0.001 B2 = 0.02* B3 = -0.0006	122.3	0.08	0.17

* indicates that $P < 0.05$ for variable in each model. Higher Akaike weights indicate increased probability of model being best fit of all candidate models. Maximum likelihood Pseudo R² calculated as $1 - (\text{Residual} / \text{Null deviance})$

Parasitoid abundance and garden area had a positive relationship (AIC = 379.2, $P = 0.05$). Two models had $\Delta\text{AICc} < 2$ for predator abundance, and all models included a positive effect of floral abundance (Table 3). Garden area and floral abundance have positive relationships with all predator taxa except for Vespidae (Electronic Supplementary Material A).

Only 16% of constrained variation in natural enemy community composition was explained by the adult and immature herbivores. There was a marginally significant effect of adult cabbageworms explaining natural enemy community composition ($F = 1.84$, $P = 0.06$). The ANOSIM indicated no significant difference in natural enemy community composition between different types of food production sites ($R = 0.04$, $P = 0.20$).

Discussion

Our study revealed the presence of insect herbivores and a diverse natural enemy community in all three food production

types. Neither defoliation nor abundance of herbivores were strongly affected by study site characteristics, and we found no support for the resource concentration hypothesis in urban agriculture. On the other hand, abundance of natural enemies was positively related to the floral resources and size of each site. In larger sites with more brassica, where we might expect to see larger pest populations, high numbers of natural enemies on sticky cards suggests they may be successfully maintaining low herbivore population sizes.

Our consistently low abundance of pests across sites of variable garden area is in agreement with Grez and Gonzalez (1995), who also noted that densities of cabbageworm larvae and aphids did not vary significantly among experimental cabbage patches that were comparable in size to our three food production types. Of all insect pests, only adult cabbageworm abundance was positively associated with number of brassica rows (Table 2). At this life stage, *P. rapae*, the most common species, feeds on nectar and prefers to visit larger gardens with more

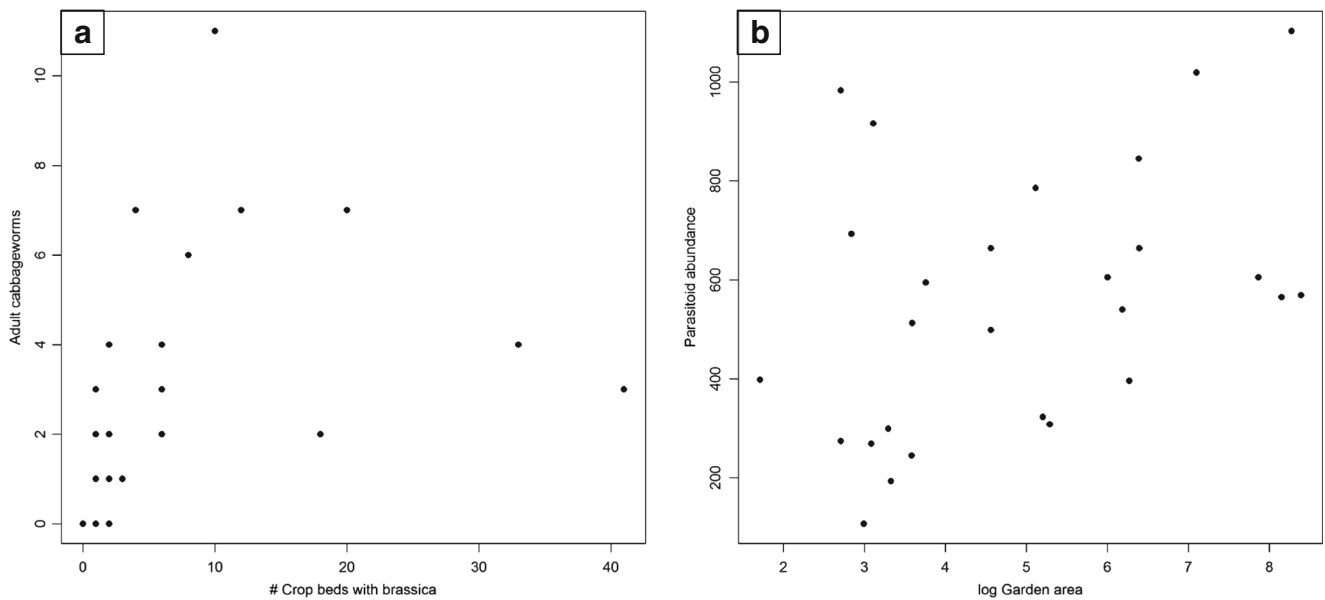


Fig. 2 Local garden characteristics identified from model selection that influenced adult cabbageworms (a) and parasitoids (b) in brassica crops

flowers (Matteson and Langellotto 2012). While large, florally-rich gardens may attract adults for nectar, they also attract natural enemy taxa that commonly prey upon the eggs and larvae rather than the adult butterflies. Adult female *P. rapae* can travel long distances (Jones et al. 1980; Fahrig and Paloheimo 1987; Talekar and Shelton 1993) and backyard gardens are ample across the city

(Taylor and Lovell 2012). Furthermore, the number of eggs laid in a patch of cultivated brassica by a female *P. rapae* has been shown to be independent of planted brassica area (Fahrig and Paloheimo 1987). Together, these pieces of information explain why we did not find strong effects of local- or landscape-level variables on cabbageworm pests. Our pest abundance findings differ

Fig. 3 Mean parasitoid (a), aphid parasitoid (b), and predator (c) abundance on yellow sticky cards in three types of agriculture in Chicago, IL (USA). Aphid parasitoids are specialists from the Aphidiinae subfamily Sample date is the start of 2-week period when sticky cards were left in each garden. Each number on the X axis corresponds to a biweekly count: 1 = 16 June 2014, 2 = 30 June 2014, 3 = 14 July 2014, 4 = 28 July 2014, 5 = 11 August 2014. Lower-case letters in plots indicate significant differences between dates in natural enemy abundance pooled across all sites

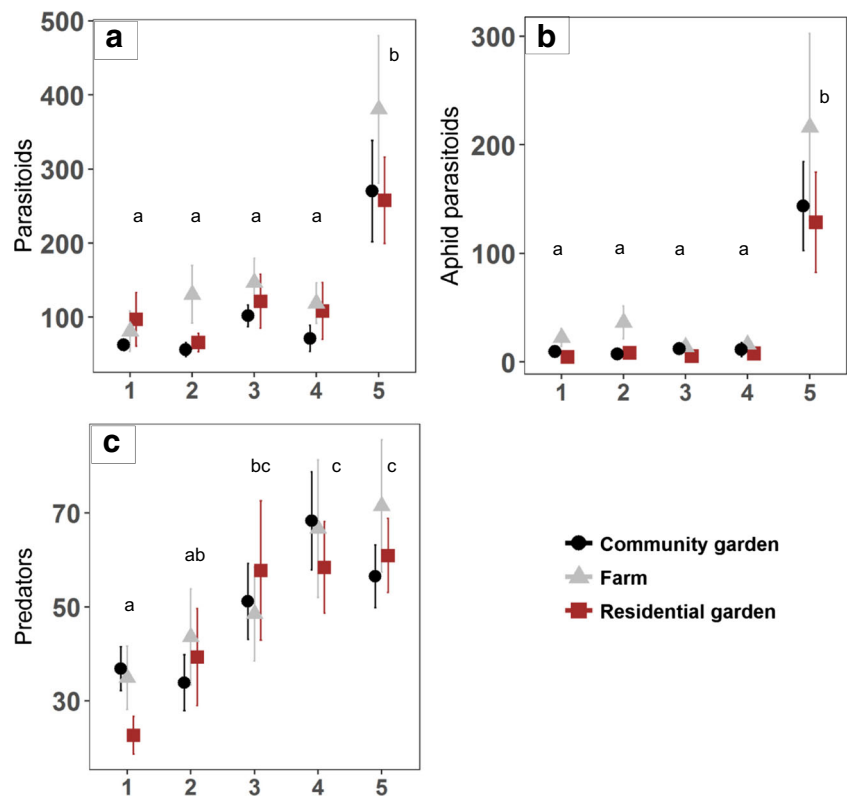


Table 3 Summary of top-performing models that explain a portion of variation in natural enemy abundance and have AICc <2

Natural enemy	Model	Coefficients	AICc	Akaike weight	Pseudo R ²
Parasitoid abundance	1. Garden area + Grass1000	B1 = 0.11* B2 = -0.03	379.0	0.26	0.21
	2. Garden area	B = 0.09*	379.2	0.24	0.18
	3. Garden area + Floral richness + Grass1000	B1 = 0.13* B2 = 0.04 B3 = -0.03	379.5	0.20	0.28
	4. Garden area + Floral richness	B1 = 0.11* B2 = 0.04	380.1	0.16	0.18
	5. Intercept		380.4	0.14	
Predator abundance	1. Floral abundance + Grass1000	B1 = 0.002** B2 = -0.03*	324.8	0.57	0.41
	2. Floral abundance + Grass1000 + Garden area	B1 = 0.002 B2 = -0.03 B3 = 0.05	325.3	0.43	0.46

* indicates $P < 0.05$ and ** indicates $P < 0.01$ for variables in each model. Higher Akaike weights indicate increased probability of model being best fit of all candidate models. Maximum likelihood Pseudo R² calculated as $1 - (\text{Residual} / \text{Null deviance})$

from those on non-urban farms, where higher counts of aphids and cabbageworms have been reported (Root 1973; Shelton et al. 1982; Maltais et al. 1998). We attribute this difference to the abundant and diverse natural enemy communities at our study sites.

Four parasitoid families and two predator families comprised 76% and 62% of the parasitoid and predator samples, respectively (Electronic Supplementary Material B). The ANOSIM analysis confirmed the overlapping distribution of parasitoid and predator families across different food production types. Natural enemy and pollinator species richness also did not vary across urban gradients in multiple Swiss cities (Sattler et al. 2010), and this similarity in community composition could be an artefact of urbanization already selecting against insect taxa incapable of surviving fragmentation and disturbance that restrict habitat availability. Speciose parasitic families, including Braconidae, Ichneumonidae, and Pteromalidae, are common in urban gardens (Bennett and Gratton 2012), contain primary and hyperparasitoids, and have a broad host range of beetles, aphids, and true bugs (Goulet and Huber 1993) that suits them well to the polycultures that attract diverse insect hosts in urban agriculture. Similarly, many predators in urban agriculture are generalists, tolerant of disturbed soils and environments (Gardiner et al. 2014; Burkman and Gardiner 2015), and have been documented to attack immature cabbageworms (Lowenstein et al. 2017).

Garden area, floral abundance, and floral richness were the most plausible factors to influence natural enemy abundance (Table 3). These proxies of resource availability enhance parasitoid abundance in other urban areas (Bennett and Gratton 2012; Burks and Philpott 2017). Flowering ornamental plants, present around the edges of all sites and sometimes within

crop rows, are a suitable resource for predators including lacewings (Jacometti et al. 2010), hover flies (White et al. 1995), and long-legged flies (Ulrich 2004). Extensive cultivation of ornamental plants in residential neighborhoods (Smith et al. 2006) extends the flowering season in cities, providing natural enemies with ample opportunities to supplement their diet near gardens.

Strong seasonality was evident for natural enemies and pests, and these patterns were consistent among the three food production types. Aphids and natural enemies were most abundant at the end of August, while cabbageworm larvae experienced a first peak at the end of June and a second peak about a month later (Fig. 1). Seasonal variation in aphid and cabbageworm populations is well-documented (Hughes 1963; Root 1973), but pest emergence dates and fecundity could be extended by the urban heat island effect (Dale and Frank 2014). Continued monitoring for pests in urban agriculture will determine if predator-prey interactions in urban agriculture are comparable to street trees, whose pests experience phenological mismatches with natural enemies and a reduction in biological control due to earlier emergence (Meineke et al. 2014).

Evidence of seasonal patterns in pest populations offers a starting point for determining the periods at greatest risk of crop damage. For example, high densities of late season-aphids may necessitate chemical inputs. The small size of urban farms—the largest in Chicago is 2.8 ha - could be insufficient to host cabbageworm populations large enough to have an economic impact. At present, low defoliation and a diverse natural enemy community at all food production types suggest a minimal risk for brassica damage in Chicago, IL food production. However, accurate measures of economic injury from pests require information on vulnerable plant stages, pest

phenology, and plant variety (Ramsden et al. 2017). Since cabbageworm abundance and parasitism can differ by *B. oleracea* cultivars and leaf structure (Pimentel 1961; Godin and Boivin 1998), future work should control for variety to better understand the risk of plant damage. If urban food production is further commercialized, our results can serve as a baseline for measuring plant injury levels that would necessitate chemical inputs or other integrated pest management strategies.

We acknowledge several limitations to this study. Yellow sticky cards are a common tool for sampling arthropods since they standardize sampling frequency and duration. However, sticky cards tend to underestimate generalist predator populations compared to foliar counts or sweep sampling (Schmidt et al. 2008). The cards are also prone to several sampling biases including greater catch of insects during blooming (Gardiner et al. 2014), a tendency to attract more mobile natural enemies (Schmidt et al. 2008), and different capture rates between lady beetle species (Musser et al. 2004). Nevertheless, yellow sticky cards in vegetable crops provide a comparable representation of parasitoids identified by direct counts in the field (Hoelmer and Simmons 2008). Additionally, daytime sampling of adult cabbageworms reduces the potential for recording nocturnal *X. plutella* and *T. ni* adults. However, the dominance of *P. rapae* in egg and larva counts suggested that other cabbageworm species are secondary pests. Future researchers may wish to identify natural enemies to the species level, which could better explain population patterns and the relationships to pests. However, challenging diagnostic features in many groups restrict identification to specialist taxonomists. Finally, our study does not identify interrelated drivers of pest abundance and cannot distinguish if herbivore abundance reflects pest management by gardeners or control by natural enemies.

While vegetable production covers a small percentage of urban land area and is distributed unevenly between neighborhoods (Taylor and Lovell 2012), its plant resources add floral and habitat diversity to areas dominated by impervious surface and turf grass. This study demonstrates the ability of urban agriculture to provide refugia, habitat, and insect hosts for natural enemies. As shrinking Midwestern (USA) cities envision new agricultural usages for vacant lots and underutilized sites (Lovell 2010), long-term brassica cultivation could influence arthropod populations by including more suitable overwintering sites needed to host specialist parasitoids (Puente et al. 2008), further increasing the capacity to support natural enemies. Our research suggests that urban food production adds an important privately-managed land use that could contribute pest suppression services to the entire city.

Acknowledgements Sharmeen Razvi and Deborah Gartshore provided field assistance. Steve Krauth assisted in parasitoid identification. Funding was provided by Ceres Trust graduate student grant, UIC Department of Biological Sciences Hadley Graduate Research Award, and UIC Chancellor's Award.

References

- Bach CE (1988) Effects of host plant patch size on herbivore density: underlying mechanisms. *Ecology* 69:1103–1117 <http://www.jstor.org/stable/1941265>
- Barton K (2015) MuMIn: Multi-model inference. R package version 1.15.1. (<http://CRAN.R-project.org/package=MuMIn>). Accessed 20 Sept 2017
- Bennett AB, Gratton C (2012) Local and landscape scale variables impact parasitoid assemblages across an urbanization gradient. *Landsc Urban Plan* 104:26–33. <https://doi.org/10.1016/j.landurbplan.2011.09.007>
- Bonnemaïson L (1965) Insect pests of crucifers and their control. *Annu Rev Entomol* 10:233–256
- Burkman CE, Gardiner MM (2014) Urban greenspace composition and landscape context influence natural enemy community composition and function. *Biol Control* 75:58–67. <https://doi.org/10.1016/j.biocontrol.2014.02.015>
- Burkman CE, Gardiner MM (2015) Spider assemblages within greenspaces of a deindustrialized landscape. *Urban Ecosystems* 18:793–818. <https://doi.org/10.1007/s11252-014-0430-8>
- Burks JM, Philpott SM (2017) Local and landscape drivers of parasitoid abundance, richness, and composition in urban gardens. *Environ Entomol* 46:201–209. <https://doi.org/10.1093/ee/nvw175>
- Capman WC, Batzli GO, Simms LE (1990) Responses of the common sooty wing skipper to patches of host plants. *Ecology* 71:1430–1440 <http://www.jstor.org/stable/1938280>
- Costamagna AC, Landis DA (2006) Predators exert top-down control of soybean aphid across a gradient of agricultural management systems. *Ecol Appl* 16:1619–1628. [https://doi.org/10.1890/1051-0761\(2006\)016\[1619:PETCOS\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2006)016[1619:PETCOS]2.0.CO;2)
- Cromartie WJ (1975) The effect of stand size and vegetational background on the colonization of cruciferous plants by herbivorous insects. *J Appl Ecol* 12:517–533
- Dale AG, Frank SD (2014) Urban warming trumps natural enemy regulation of herbivorous pests. *Ecol Appl* 24:1596–1607. <https://doi.org/10.1890/13-1961.1>
- Denno RF, Gratton C, Peterson MA, Langellotto GA, Finke DL, Huberty AF (2002) Bottom-up forces mediate natural enemy impact in a phytophagous insect community. *Ecology* 83:1443–1458. [https://doi.org/10.1890/0012-9658\(2002\)083\[1443:BUFMNE\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2002)083[1443:BUFMNE]2.0.CO;2)
- Egerer MH, Bichier P, Philpott SM (2016) Landscape and local habitat correlates of lady beetle abundance and species richness in urban agriculture. *Ann Entomol Soc Am* 110:97–103. <https://doi.org/10.1093/aesa/saw063>
- Fahrig L, Paloheimo JE (1987) Interpatch dispersal of the cabbage butterfly. *Can J Zool* 65:616–622
- Fuller RA, Irvine KN, Devine-Wright P, Warren PH, Gaston KJ (2007) Psychological benefits of greenspace increase with biodiversity. *Biol Lett* 3:390–394. <https://doi.org/10.1098/rsbl.2007.0149>
- Gardiner MM, Prajzner SP, Burkman CE, Albro S, Grewal PS (2014) Vacant land conversion to community gardens: influences on generalist arthropod predators and biocontrol services in urban greenspaces. *Urban Ecosystems* 17:101–122. <https://doi.org/10.1007/s11252-013-0303-6>

- Godin C, Boivin G (1998) Lepidopterous pests of *Brassica* crops and their parasitoids in Southwestern Quebec. *Environ Entomol* 27: 1157–1165
- Goulet H, Huber J (1993) Hymenoptera of the world: an identification guide to families. Agriculture Canada Publication, Ottawa, p 698
- Gregory MM, Leslie TW, Drinkwater LE (2016) Agroecological and social characteristics of New York city community gardens: contributions to urban food security, ecosystem services, and environmental education. *Urban Ecosystems* 19:763–794. <https://doi.org/10.1007/s11252-015-0505-1>
- Grewal SS, Grewal PH (2012) Can cities become self-reliant in food? *Cities* 29:1–11. <https://doi.org/10.1016/j.cities.2011.06.003>
- Greze AA, Gonzalez RH (1995) Resource concentration hypothesis: effect of host plant patch size on density of herbivorous insects. *Oecologia* 103:471–474. <https://doi.org/10.1007/BF00328685>
- Hamback PA, Englund G (2005) Patch area, population density, and the scaling of migration rates: the resource concentration hypothesis revisited. *Ecol Lett* 8:1057–1065. <https://doi.org/10.1111/j.1461-0248.2005.00811.x>
- Hoelmer KA, Simmons AM (2008) Yellow sticky trap catches of parasitoids of *Bemisia tabaci* in vegetable crops and their relationship to in-field populations. *Environ Entomol* 37:391–399. [https://doi.org/10.1603/0046-225X\(2008\)37\[391:YSTCOP\]2.0.CO;2](https://doi.org/10.1603/0046-225X(2008)37[391:YSTCOP]2.0.CO;2)
- Hughes RD (1963) Population dynamics of the cabbage aphid, *Brevicoryne brassicae*. *J Anim Ecol* 32:393–424
- Jacometti M, Jorgensen N, Wratten S (2010) Enhancing biological control by an omnivorous lacewing: Floral resources reduce aphid numbers at low densities. *Biol Control* 55:159–165. <https://doi.org/10.1016/j.biocontrol.2010.09.001>
- Jones R, Gilbert N, Guppy M, Nealis V (1980) Long-distance movement of *Pieris rapae*. *J Anim Ecol* 49:629–642 <http://www.jstor.org/stable/4268>
- Kareiva P (1985) Finding and losing host plants by Phyllostreta: patch size and surrounding habitat. *Ecology* 66:1809–1816 <http://www.jstor.org/stable/2937376>
- Lin BB, Philpott SM, Jha S (2015) The future of urban agriculture and biodiversity-ecosystem services: Challenges and next steps. *Basic Appl Ecol* 16:189–201. <https://doi.org/10.1016/j.baae.2015.01.005>
- Lovell ST (2010) Multifunctional urban agriculture for sustainable land use planning in the United States. *Sustain For* 2:2499–2522. <https://doi.org/10.3390/su2082499>
- Lowenstein DM, Matteson KC, Minor EM (2015) Diversity of wild bees supports pollination services in an urbanized landscape. *Oecologia* 179:811–821
- Lowenstein DM, Gharehaghaji M, Wise D (2017) Substantial mortality of cabbage looper from predators in urban agriculture is not influenced by scale of production or variation in local and landscape-level factors. *Environ Entomol* 46:30–37. <https://doi.org/10.1093/ee/nvw147>
- Maltais PM, Nuckle JR, Leblanc PV (1998) Economic threshold for three lepidopterous larval pests of fresh-market cabbage in southeastern New Brunswick. *J Econ Entomol* 91:699–707. <https://doi.org/10.1093/jee/91.3.699>
- Mata L, Threlfall CG, Williams NSG, Hahs AK, Malipatil M, Stork NE, Livesley SJ (2017) Conserving herbivorous and predatory insects in urban green spaces. *Sci Rep – UK* 7:40970. <https://doi.org/10.1038/srep40970>
- Matteson KC, Langellotto GA (2012) Evaluating community gardens as habitat for an urban butterfly. *Cities Environ* 5(10):1–14 <http://digitalcommons.lmu.edu/cate/vol5/iss1/10>
- Meineke EK, Dunn RR, Frank SD (2014) Early pest development and loss of biological control are associated with urban warming. *Biol Lett* 10:20140586. <https://doi.org/10.1098/rsbl.2014.0586>
- Mok H, Williamson VG, Grove JR, Burry K, Barker SF, Hamilton AJ (2014) Strawberry fields forever? Urban agriculture in developed countries: a review. *Agron Sustain Dev* 34:21–43. <https://doi.org/10.1007/s13593-013-0156-7>
- Musser FR, Nyrop JP, Shelton AM (2004) Survey of predators and sampling method comparisons in sweet corn. *J Econ Entomol* 97:136–144. <https://doi.org/10.1603/0022-0493-97.1.136>
- Oksanen J et al (2016) Vegan community ecology package. R package version 2.4 <https://CRAN.R-project.org/package=vegan>
- Otoshi MD, Bichier P, Philpott SM (2015) Local and landscape correlates of spider activity density and species richness in urban gardens. *Environ Entomol* 44:1043–1051. <https://doi.org/10.1093/ee/nvv098>
- Philpott SM, Bichier P (2017) Local and landscape drivers of predation services in urban gardens. *Ecol Appl* 27:966–976. <https://doi.org/10.1002/eap.1500>
- Philpott SM, Cotton J, Bichier P, Friedrich RL, Moorhead LC, Uno S, Valdez M (2014) Local and landscape drivers of arthropod abundance, richness, and trophic composition in urban habitats. *Urban Ecosystems* 17:513–532. <https://doi.org/10.1007/s11252-013-0333-0>
- Pimentel D (1961) The influence of plant spatial patterns on insect populations. *Environ Entomol* 54:61–69
- Puente M, Magori J, Kennedy GG, Gould F (2008) Impact of herbivore-induced plant volatiles on parasitoid foraging success: a spatial simulation of the *Cotesia rubecula*, *Pieris rapae*, and *Brassica oleracea* system. *J Chem Ecol* 34:959–970. <https://doi.org/10.1007/s10886-008-9472-9>
- R Development Core Team (2015) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna
- Ramsden MW, Kendall SL, Ellis SA, Berry PM (2017) A review of economic thresholds for invertebrate pests in UK agriculture. *Crop Prot* 96:30–43. <https://doi.org/10.1016/j.cropro.2017.01.009>
- Richards OW (1940) The biology of the small white butterfly (*Pieris rapae*) with special reference to factors controlling its abundance. *J Anim Ecol* 9:243–288
- Root RB (1973) Organization of a Plant-Arthropod Association in simple and diverse habitats: The fauna of collards (*Brassica oleracea*). *Ecol Monogr* 43:95–124
- Sattler T, Duelli P, Obrist MK, Arlettaz R, Morreti M (2010) Response of arthropod species richness and functional groups to urban habitat structure and management. *Landsc Ecol* 25:941–954. <https://doi.org/10.1007/s10980-010-9473-2>
- Schmaedick MA, Shelton AM (1999) Experimental evaluation of arthropod predation on *Pieris rapae* (Lepidoptera:Pieridae) eggs and larvae in cabbage. *Environ Entomol* 28:439–444. <https://doi.org/10.1093/ee/28.3.439>
- Schmidt NP, O'neal MO, Dixon PM (2008) Aphidophagous predators in Iowa soybean: a community comparison across multiple years and sampling methods. *Ann Entomol Soc Am* 101:341–350. [https://doi.org/10.1603/0013-8746\(2008\)101\[341:APIISA\]2.0.CO;2](https://doi.org/10.1603/0013-8746(2008)101[341:APIISA]2.0.CO;2)
- Shelton AM, Andaloro JT, Barnard J (1982) Effects of cabbage Looper, imported cabbageworm, and diamondback moth on fresh market and processing cabbage. *J Econ Entomol* 75:742–745. <https://doi.org/10.1093/jee/75.4.742>
- Shelton AM, Wilsley WT, Hoebeke ER, Schmaedick MA (2002) Parasitoids of cabbage Lepidoptera in Central New York. *J Entomol Sci* 37:270–271
- Shrewsbury PM, Raupp MJ (2006) Do top-down or bottom-up forces determine *Stephanitis Pyrioides* abundance in urban landscapes? *Ecol Appl* 16:262–272. <https://doi.org/10.1890/04-1347>
- Smith RM, Thompson K, Hodgson JG, Warren PH, Gaston KG (2006) Urban domestic gardens (IX): composition and richness of the vascular plant flora, and implications for native biodiversity. *Biol Conserv* 129:312–322. <https://doi.org/10.1016/j.biocon.2005.10.045>
- Snyder WE, Snyder GB, Finke DL, Straub CS (2006) Predator biodiversity strengthens herbivore suppression. *Ecol Lett* 9:789–796. <https://doi.org/10.1111/j.1461-0248.2006.00922.x>

- Talekar NS, Shelton AM (1993) Biology, ecology, and management of the diamondback moth. *Annu Rev Entomol* 38:275–301. <https://doi.org/10.1146/annurev.en.38.010193.001423>
- Taylor JT, Lovell ST (2012) Mapping public and private spaces in urban agriculture in Chicago through the analysis of high-resolution aerial images in Google earth. *Landsc Urban Plan* 108:57–70. <https://doi.org/10.1016/j.landurbplan.2012.08.001>
- Taylor JT, Lovell ST (2014) Urban home food gardens in the global north: research traditions and future directions. *Agric Hum Values* 31(2):85–305. <https://doi.org/10.1007/s10460-013-9475-1>
- Taylor JT, Lovell ST, Wortman SE, Chan M (2016) Ecosystem services and tradeoffs in the home food gardens of African American, Chinese-origin, and Mexican-origin households in Chicago, IL. *Renew Agric Food Syst* 32:69–86. <https://doi.org/10.1017/S174217051600003X>
- Tornaghi C (2014) Critical geography of urban agriculture. *Prog Hum Geogr* 38:551–567. <https://doi.org/10.1177/0309132513512542>
- Ulrich H (2004) Predation by adult Dolichopodidae (Diptera): a review of literature with an annotated prey-predator list. *Studia Dipterologica* 11:369–403
- Walker M, Jones TH (2001) Relative roles of top-down and bottom-up forces in terrestrial Tritrophic plant-insect herbivore-natural enemy systems. *Oikos* 93:177–187. <https://doi.org/10.1034/j.1600-0706.2001.930201.x>
- White AJ, Wratten SD, Berry NA, Weigmann U (1995) Habitat manipulation to enhance biological control of *Brassica* pests by hover flies (Diptera: Syrphidae). *J Econ Entomol* 88:1171–1176. <https://doi.org/10.1093/jee/88.5.1171>
- Zeza A, Tasciotti L (2010) Urban agriculture, poverty, and food security: Empirical evidence from a sample of developing countries. *Food Policy* 35:265–273. <https://doi.org/10.1016/j.foodpol.2010.04.007>