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Research

Biological Control–Weeds

The Effect of Conservation Tillage and Cover Crop Residue on Beneficial Arthropods and Weed Seed Predation in Acorn Squash

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Abstract

Conservation tillage combined with cover crops or mulching may enhance natural enemy activity in agroecosystems by reducing soil disturbance and increasing habitat structural complexity. In particular, weed seed predation can increase with vegetation cover and reduced tillage, indicating that mulches may improve the quality of the habitat for weed seed foraging. The purpose of this study was to quantify the effects of tillage and mulching for conservation biological control in cucurbit fields. The effects of mulch and reduced tillage on arthropods and rates of weed seed loss from arenas were examined in field trials on sandy soils in 2014 and 2015. Experimental factors included tillage and cover crop, each with two levels: strip-tillage or full-tillage, and cover crop mulch (rye residue) or no cover crop mulch (unmulched). Arthropod abundance on the crop foliage was not affected by tillage or cover crops. Contrary to expectations, epigeal natural enemies of insects and rates of weed seed removal either did not respond to treatments or were greater in full-tilled plots and plots without mulch. Our study demonstrates the potential importance of weed seed predators in reducing weed seedbanks in vegetable agroecosystems, and suggests that early-season tillage may not be detrimental to epigeal predator assemblages.

Key words: habitat management, Carabidae, granivory, no-till, epigeal

Farmers often use conservation tillage techniques, such as strip-tillage, and mulches to protect soil quality by reducing runoff, erosion, and soil compaction (Gebhardt et al. 1985, Luna et al. 2012). In addition to these agronomic benefits, conservation tillage with cover crop mulches may enhance natural enemy activity by reducing soil disturbance and increasing habitat structural complexity at the soil surface (Landis et al. 2000, Langellotto and Denno 2004, Menalled et al. 2007, Blubaugh and Kaplan 2015). Strip-tillage systems, which include both disturbed and undisturbed zones within the same field, add complexity which may favor more diverse insect and weed communities relative to both full-tillage and no-tillage (Brainard et al. 2013). Mulching can provide nesting habitat, shelter, and favorable microclimate to arthropods near the soil surface, which can lead to higher natural enemy abundance (Hooks et al. 2011, Bryant et al. 2013) and performance on crops (Lundgren and Fergen 2010, Bryant et al. 2013).

Insects such as ground beetles (Carabidae) and crickets (Gryllidae) can be important sources of weed seed and insect pest mortality in agricultural systems (Rebek et al. 2005, O'Rourke et al. 2006, Westerman et al. 2008, Baraibar et al. 2011, Bagavathiannan and Northsworthy 2013, Lundgren et al. 2013), and their impact is often strongly influenced by tillage and mulching practices. Peak foraging activity of several granivorous adult carabid species occurs in the fall, synchronized with the release of grass seeds (Tooley and Brust 2002). Under reduced-tillage systems, the percentage of weed seeds at or near the soil surface is greater than in conventional tillage systems (Yenish et al., 1992). Since seed predation rates decline rapidly with depth of burial in the soil for most seed predators (e.g., Rodríguez and Garcia 2009), shallow distribution of seeds under reduced tillage favors higher rates of predation (Baraibar et al. 2012, Eyre et al. 2013). Weed seed predation can increase with vegetation cover, indicating that mulches may improve the quality of the habitat for weed seed foraging (Meiss et al. 2010). However, the effects of tillage and residue management on granivory are highly variable. Although several studies report higher rates of invertebrate predation under conservation agricultural practices (Brust and House 1988, Kromp 1999, Purvis and Fadl 2002), other studies report greater granivore activity density and lower weed pressure under conventional tillage (Liebman and Davis 2000, Westerman et al. 2008, van der Laat et al. 2015). Taken together, the literature suggests that invertebrate granivores can be effective predators of newly dispersed weed seeds in agricultural settings, but that their impact and interactions with tillage and mulching practices can vary substantially across cropping systems.

Weeds also represent a major constraint to successful production in cucurbit cropping systems. Weeds can compete directly with the crop (e.g., Johnson and Mullinix 1998), serve as alternate hosts of insect and disease pests (e.g., French-Monar et al. 2006), and produce large quantities of seeds that negatively impact rotational crops (Swinton and King 1994, Brainard and Bellinder 2004). Although management of weeds is typically accomplished through curative approaches including herbicides and mechanical cultivation, practices that encourage seed predation and decay can be helpful for reducing problematic weeds as part of an integrated weed management program (Gallandt 2006).

Cucurbits are an economically important crop in the United States, with about 40% of the country's cucurbits grown in the Midwest (USDA-NASS 2013). Expenditures for pest insect, weed, and disease management in these crops can exceed US$100 per acre in a growing season for pesticide applications alone (Barnett 2012). Despite these costs, yield losses due to pests remain high (Schmidt et al. 2014, USDA-NASS 2014), justifying the need to explore management methods that can contribute to sustainable pest reduction.

The aim of this study was to quantify the effects of conservation tillage and mulching on the arthropod community and weed seed predation in acorn squash (*Cucurbita pepo* var. turbinata) over two growing seasons in Michigan. We set up four different levels of disturbance and habitat complexity to test the hypothesis that mulching and reduced tillage would decrease herbivores on the crop, increase natural enemy abundance and activity, and increase predation of weed seeds in an experimental field.

Materials and Methods

Field Plots

The field trial on reduced tillage and mulching took place at the Southwest Michigan Research and Extension Center in Benton Harbor, MI (42° 4'57.01″ N, 86° 21'16.13″ W) in 2014 and 2015 in two separate fields ~265 m apart, both with an Oakville fine sand soil (Mixed, mesic Typic Udipsamments). Major field plot operations are summarized in Supp. Table 1 [online only]. The experiments in both years had four treatments, a combination of tillage and ground cover factors, each with two levels: strip-tillage or full-tillage, and cover crop mulch (rye residue) or no cover crop mulch (unmulched). In strip-tilled plots, tillage only occurred in the row where the crop was planted and the area between crop-rows was left undisturbed. Treatments were organized in a split plot design with six replications. Tillage was the main plot factor, and cover crop mulch was the subplot factor. Due to insufficient rye biomass production in both years, additional rye mulch was added to the cover crop treatment plots before tilling at a rate of 0.41 kg/m^2. In all plots, 19-19-19 (N-P-K) fertilizer at a rate of 86.25 kg/ha was applied before planting. The entire field was then direct seeded with acorn squash (*Cucurbita pepo* var. turbinata, "Autumn Delight", 2014: Seigers Seed Company, Holland, MI; 2015: SeedWay, Hall, NY) using a Matermacc Magicsem series 8000 precision vacuum planter (Via Gemona, 18, 33078 San Vito al Tagliamento, PN, Italy). Squash seeds were placed 40 cm apart within the rows with 1.5 m separating the rows. Individual plots were 5.5 by 15 m and contained three rows of acorn squash. Insecticides were not used, but fungicides were applied according to standard grower practices. Weeds were managed using: 1) glyphosate (2.24 kg ai/ha) applied in early spring to kill the rye cover crop and winter annual and perennial weeds established prior to planting winter squash, 2) pre-emergence applications of ethalfluralin (0.67 kg ai/ha), clomazone (0.21 kg ai/ha), and s-metolachlor (1.06 kg ai/ha) applied 3–4 d after crop planting, and 3) hand-weeding to maintain weeds escaping herbicide treatments. This approach was highly effective in maintaining essentially weed-free conditions throughout the growing season, although several plots required frequent soil-surface disturbance with hoes to manage the perennial weeds horsenettle (*Solanum carolinense*) and quackgrass (*Elymus repens*).

Foliar Arthropod Sampling

To determine the effects of tillage and mulching treatments on arthropods, we visually surveyed foliage during the growing seasons in the center row of each plot on 10 randomly selected whole plants during the first two weeks following squash emergence. Once the plants had approximately five leaves each, the numbers of arthropods on 10 randomly selected squash leaves in the central row were recorded weekly between June 26–August 20, 2014 and July 2–August 21, 2015 (8 wk in 2014 and 7 wk in 2015). Arthropods were identified to order or family in the field and classified as herbivores or natural enemies.

Activity Density Sampling

Pitfall traps were deployed throughout the growing season in 2014 and 2015 (between the same dates as above). Two pitfall traps per plot were placed 3 m apart in the center of the plot slightly offset from the central squash row. The traps were constructed from 946 ml cups (Dart Container Corporation, Mason MI) containing ~200 ml of a propylene glycol and water solution (1:1 v/v). Traps were covered with metal lids, to protect them from rain, which were raised ~4 cm above the lip of the trap. Pitfall traps were deployed for a week (± 1 d), after which the contents were strained in the field through gauze. Samples from individual traps were preserved in 75% ethanol, then stored at −20 °C in lab. Arthropods from pitfall traps were identified under a microscope to order or family in the laboratory (Marshall 2006, Bousquet 2010, Albert J. Cook Arthropod Research Collection).

Weed Seed Predation

To determine the activity density of weed seed predators, the disappearance of sentinel weed seeds from the field plots on three dates at the end of the growing season in 2014 and 2015 was evaluated as a proxy for granivory in each treatment. Three species of commonly occurring weed seeds were used: Powell amaranth (*Amaranthus powellii)*, common lambsquarters (*Chenopodium album*), and giant foxtail (*Setaria faberi)*. In each plot, seeds of each species were deployed in separate 15-cm-diameter Petri dish arenas (VWR International, Radnor, PA). Seeds in arenas were placed on the surface of 100 ml general-purpose sand (KolorScape, Oldcastle Materials, Atlanta, GA); dishes were buried such that the lip of the Petri dish was flush with the soil surface. Each arena contained 100 seeds of a single weed species (5,659 seeds/m^2) as counted with a Seedboro Model 801 COUNT-A-PAK Seed Counter (Seedburo Equipment Co., Des Plaines, IL). For comparison, the surface (0–3 cm) density of germinable summer annual weed species in neighboring fields under similar management ranged from ~1,500 to 2,000 seeds/m^2 as determined by exhaustive germination in a greenhouse (D.C.B., unpublished data). Given that seeds of many winter annual weeds, and dormant seeds of summer annuals are not accounted for by this method, the seed density used in this trial was likely similar to ambient weed seed densities in the field, and thus minimized possible density-dependent inflation of predation rates (Cardina et al. 1996, Shuler et al. 2008). Three petri dish arenas, one for each weed species, were placed at the center of each plot. Two pitfall traps per plot were deployed concurrently, as described previously, to measure weed predator activity density. Weed arenas and pitfall traps were collected from the field after 48 h. No rainfall occurred during the period of deployment. Sampling took place on September 6–8 and 23–25 in 2014. In 2015, sampling occurred on August 26–28, August 31–September 2, September 5–7, and September 13–15. Remaining weed seeds were retrieved from the field, frozen at −20 °C to prevent germination and kill any other organisms inside arenas. The arenas were allowed to dry at room temperature for 48 h before sifting. Powell amaranth and common lambsquarters seeds were separated from the sand using a standard #35, 500-micron sieve. A #30, 600-micron sieve was used to isolate the giant foxtail seeds. The number of remaining fully intact weed seeds were counted under a microscope and recorded. Pitfall traps were collected and processed as described previously.

Statistical Analysis

Arthropod abundance was analyzed by taxonomic groups (22 groups for foliar and 30 groups for pitfall arthropods) and sampling method with Generalized Linear Mixed Models using Laplace approximation and Poisson distribution with tillage and mulch as main effects. Data from 2014 and 2015 were analyzed separately. The interaction of tillage, mulch, and sampling date within a season by response were nested within block as random effects. Due to a significant date effect, but low sample size for each individual date, the data were combined into three temporal bins: early (weeks 1–2), mid (weeks 3–5), and late (weeks 6–8) season. Where main effects were significant ($\alpha = 0.05$), pairwise Tukey–Kramer adjusted least-square means tests were performed to determine differences among treatments (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC).

Differences in seed survival and seed predator abundance were analyzed by taxonomic group and sampling method with Generalized Linear Mixed Models using Laplace approximation and Poisson distribution. Tillage and mulch treatments and their interactions were included as fixed effects in the model. Date was nested within block as a random effect. Where main effects were significant ($\alpha = 0.05$), pairwise Tukey–Kramer adjusted least-square means tests were performed to determine differences among treatments (PROC GLIMMIX, SAS 9.4, SAS Institute, Cary, NC). The activity density of Gryllidae and *Harpalus* spp. and seed removal by treatment and year during seed predation trials were correlated using Pearson correlation coefficients for responses that exhibited significant differences according to generalized linear mixed models (PROC CORR, SAS 9.4, SAS Institute, Cary, NC).

Results

Foliar Arthropod Sampling

In 2014, a total of 2,656 insects of varying life stages were observed on the squash leaves over all of the treatments. Of these, 73 were natural enemies and 2,557 were herbivores. The most frequently observed natural enemies were green lacewings (Chrysopidae; $n = 19$) and ants (Formicidae; $n = 14$). Less than 10 individuals were observed during the season from Lampyridae ($n = 1$), Nabidae ($n = 4$), Pentatomidae ($n = 4$), Coccinellidae ($n = 8$), Anthocoridae ($n = 8$), Araneae ($n = 7$), and Parasitica ($n = 8$). Ninety-one percent of all insects recorded during foliar sampling were aphids (Aphididae), the majority of which were recorded in August 2014 during an aphid outbreak. Tillage treatment did not affect the abundance of the foliar herbivores ($F_{1,28} < 0.17$, $P > 0.05$) or natural enemies ($F_{1,28} < 0.19$, $P > 0.05$). Mulch did not affect the abundance of the foliar herbivores ($F_{1,28} < 0.17$, $P > 0.05$) or natural enemies ($F_{1,28} < 0.19$, $P > 0.05$). The interaction of tillage and mulch was not significant for herbivores ($F_{1,28} < 1.57$, $P > 0.05$) or natural enemies ($F_{1,28} < 0.19$, $P > 0.05$).

Fewer arthropods were observed on squash leaves in 2015. Of the 746 arthropods observed, the most frequently encountered were thrips ($n = 453$), aphids ($n = 111$), and squash bugs (*Anasa tristis*; $n = 44$). Natural enemies accounted for only 7% ($n = 53$) of the total arthropods encountered. We observed Dolicopodidae ($n = 17$), Anthocoridae ($n = 14$), Staphylinidae ($n = 7$), and Parasitica ($n = 15$) on the foliage during the season. Tillage and mulch treatments did not significantly affect the abundance of herbivores or natural enemies observed on squash leaves at any point in the season ($F_{1,459} < 1.92$, $P > 0.05$).

Weekly Activity Density Sampling

A total of 14,761 arthropods were captured in pitfall traps in the 2014 season. Out of these, 26% were springtails (Collembola; $n = 7{,}570$), 13% were ants (Formicidae; $n = 3{,}357$), 11% were rove beetles (Staphylinidae; $n = 2{,}957$), 7% were spiders (Araneae; $n = 1{,}763$), and 5% were ground beetles (Carabidae; $n = 1{,}242$). In 2014, adult carabids had significantly higher activity densities in full-tilled plots compared to strip-tilled plots in July, early in the season ($F_{1,77} = 4.67$, $P < 0.04$; Fig. 1a). Mulch treatment did not affect early season carabid activity density ($F_{1,77} = 0.01$, $P > 0.05$; Fig. 1a). Mulch, tillage, and the interaction of mulch and tillage did not affect mid-season carabid activity density ($F_{1,55} < 1.98$, $P > 0.05$; Fig. 1a). The activity density of carabids found late in the season was not affected by tillage ($F_{1,77} = 0.2$, $P > 0.05$; Fig. 1a). However, unmulched plots had significantly greater carabid activity density for late season dates than unmulched plots ($F_{1,77} > 6.5$, $P < 0.02$). The interaction between tillage and mulch treatment was not significant for carabid activity density during the entire season ($F_{1,32} < 8.2$, $P > 0.05$; Fig. 1a). In 2014, the majority of carabids collected were of the genus *Harpalus* (51%, $n = 635$). Early-season activity density of *Harpalus* spp. was not significantly affected by tillage, mulching, or their interaction ($F_{1,27} < 1.18$, $P > 0.05$; Fig. 1b). Mid-season activity density of *Harpalus* spp. was marginally significantly increased in unmulched plots ($F_{1,32} > 7.38$, $P < 0.07$; Fig. 1b). Late-season *Harpalus* spp. activity density was significantly increased in full-tilled unmulched plots compared to strip-tilled mulched plots ($t = 3.10$, df $= 92$, $P < 0.01$; Fig. 1b). The activity densities of all other arthropods were not significantly affected by tillage or mulch treatment or their interaction at any point during the 2014 season ($F_{1,32} < 1.32$, $P > 0.05$, Fig. 1c, d).

In 2015, a total of 24,785 arthropods were collected in pitfall traps: Collembola (33%; $n = 8{,}292$), Staphylinidae (15%; $n = 3{,}857$), Formicidae (12%; $n = 2{,}998$), Gryllidae (6%; $n = 1{,}549$), Carabidae (3%; $n = 864$), and Araneae (2.7%; $n = 688$) were the most frequently captured arthropods. Of the carabids captured, 64% of them were identified as members of the genus *Harpalus* ($n = 551$). In 2015, treatment effects on carabids were only significant early in the season ($F_{1,66} > 4.67$, $P < 0.01$). The activity density of adult carabids was significantly greater in full-tilled plots than strip-tilled plots early in the season ($t = 6.74$, df $= 66$, $P < 0.01$; Fig. 1e). Treatments did not significantly affect the activity density of *Harpalus* spp. ($F_{1,32} < 1.32$, $P > 0.05$, Fig. 1f). Significantly more spiders, crickets, and grasshoppers

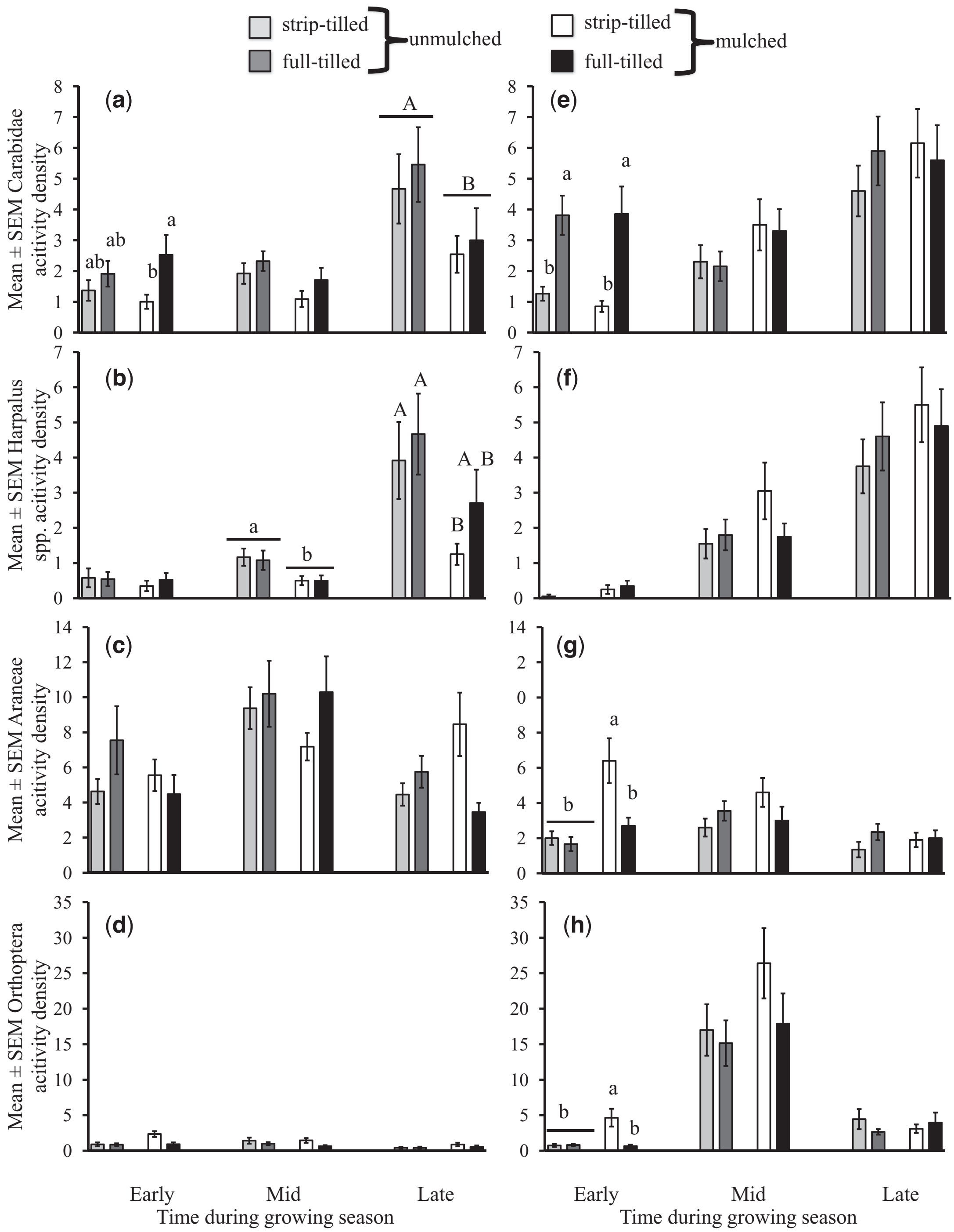

Fig. 1. Mean (±SEM) number of arthropods (activity density) collected in weekly pitfall traps by time period in 2014 (**a**, **b**, **c**, **d**) and 2015 (**e**, **f**, **g**, **h**) growing seasons. Traps were deployed in plots that were strip-tilled or full-tilled, with no rye mulch added (unmulched) or with 0.5 m^2 rye mulch added (mulched). Significant differences are indicated with different letters of the same case (Tukey's HSD, $\alpha = 0.05$).

were observed in early season strip-tilled mulched plots compared to unmulched plots with either strip or full-tillage ($t < 8.02$, $df = 66$, $P < 0.05$; Figs. 1g, 1h).

Weed Seed Predation

In 2014, a total of 203 arthropods were captured during the weed seed predation trials. The majority of specimens captured included spiders (Araneae, 17%) and ground beetles (Carabidae, 47%), with 27% of all arthropods belonging to the *Harpalus* genus. *Harpalus* spp. had significantly higher activity densities in unmulched plots than in mulched plots ($t = 2.74$, $df = 21$, $P = 0.02$; Fig. 2a). The activity densities of Staphylinidae in 2014 was not significantly affected by tillage, mulch, or their interaction ($F_{1,41} < 7.30$, $P > 0.05$; Fig. 2b). The activity density of Gryllidae was significantly greater in strip-tilled mulched plots than in full tilled unmulched plots ($t = 2.85$, $df = 59$, $P < 0.01$; Fig. 2c).

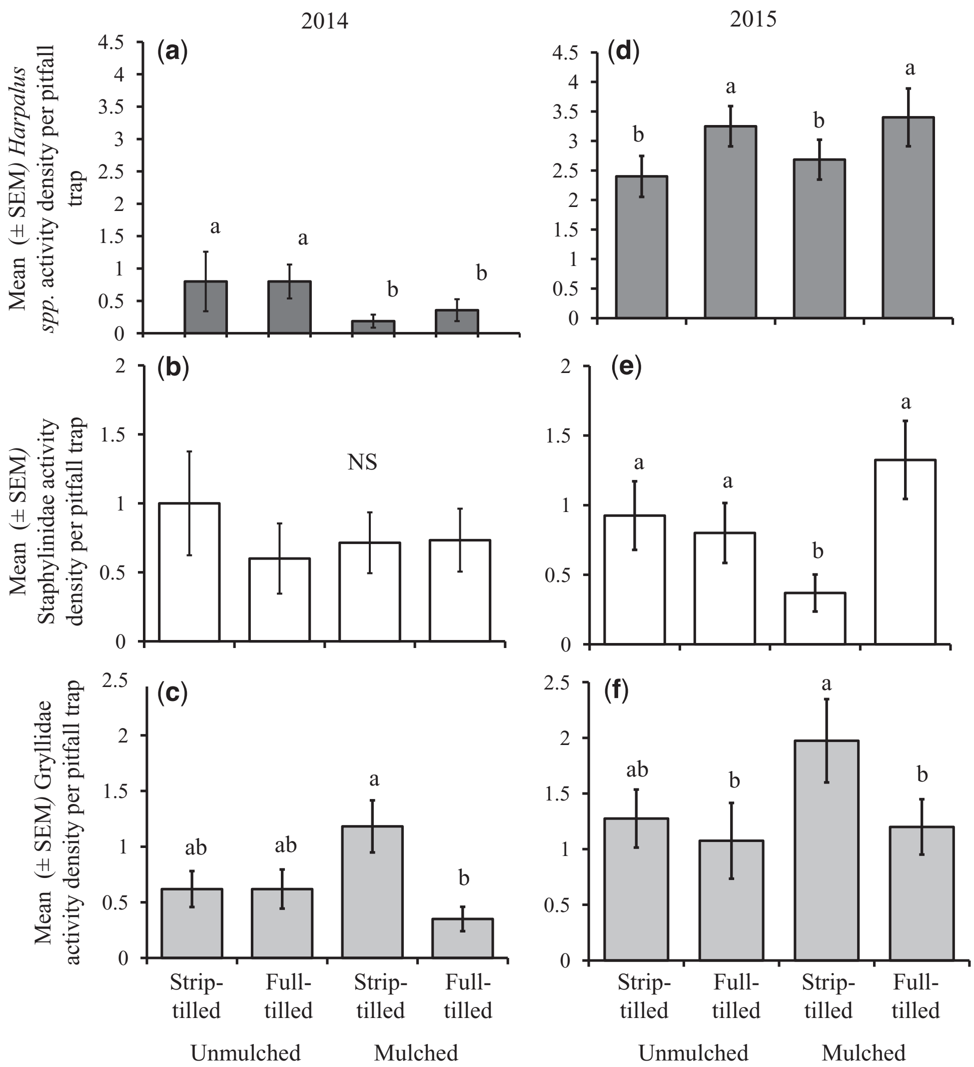

Fig. 2. Mean (±SEM) number of arthropods (activity density) collected in seed predation pitfall traps in 2014 (**a**, **b**, **c**) and 2015 (**d**, **e**, **f**) growing seasons. Traps were deployed in plots that were strip-tilled or full-tilled, with no rye mulch added (unmulched) or with 0.5 m^2 rye mulch added (mulched) concurrently with seed arenas. Significant differences are indicated with different letters (Tukey's HSD, $\alpha = 0.05$).

In 2015, a total of 2,653 arthropods were captured during weed seed predation trials over four sampling dates. The majority of specimens captured were Collembola (20%), Formicidae (18%), and *Harpalus* spp. (15%). *Harpalus* spp. had significantly higher activity densities in full-tilled plots than in strip-tilled plots ($t = 2.24$, df = 115, $P < 0.03$; Fig. 2d). Staphylinidae demonstrated significantly higher activity densities in full-tilled mulched plots than in strip-tilled and unmulched plots ($t = 0.34$, df = 115, $P < 0.01$, Fig 2e). Gryllidae demonstrated significantly higher activity densities in strip-tilled plots than in full-tilled plots ($t = 2.83$, df = 115, $P < 0.03$; Fig. 2f).

In 2014, *A. powellii* and *C. album* seed removal were not significantly affected by tillage or mulch treatment ($F_{1,17} < 0.38$, $P > 0.05$; Fig. 3a). There were significantly more *S. faberi* seeds removed from strip-tilled plots compared to full-tilled plots, regardless of mulch treatment ($t = -3.14$, df = 17, $P < 0.01$; Fig. 3a). In 2015, significantly more *A. powellii* seeds were removed from unmulched plots than in mulched plots, regardless of tillage ($t = -4.31$, df = 54, $P < 0.01$; Fig. 3b). Significantly more *C. album* seeds were removed from full-tilled unmulched plots than strip tilled mulched plots ($t = -5.43$, df = 58, $P < 0.01$; Fig. 3b). Survival of *S. faberi* was not affected by treatment ($F_{1,55} < 4.95$, $P > 0.05$).

Setaria faberi seed removal and *Harpalus* spp. activity density were not correlated in 2014 and 2015 ($R^2 < 0.7$, df = 6, $P > 0.05$). *Chenopodium album* seed removal and *Harpalus* spp. activity density were not correlated in 2014 or 2015 ($R^2 < 0.5$, df = 7, $P > 0.05$). *Setaria faberi* seed removal and Gryllidae activity density were not correlated in 2014 or 2015 ($R^2 < 0.7$, df = 7, $P > 0.05$). *Chenopodium album* seed removal and Gryllidae activity density were not correlated in 2014 or 2015 ($R^2 < 0.5$, df = 19, $P > 0.05$).

Discussion

Our 2-yr study did not support the hypothesis that pest abundance on crops decreases and natural enemy abundance increases in less disturbed and more diverse agroecosystems, as foliar arthropods did not respond to the reduced tillage and mulch treatments. In contrast to our findings, reduced tillage and mulching has been shown to reduce foliar herbivore populations presumably by improving within-field natural enemy activity and biological control (Tonhasca and Byrne 1994, Langellotto and Denno 2004, Bryant et al. 2013, Hinds and Hooks 2013). In general, insect abundance on the squash was relatively low in our experimental field during the study period,

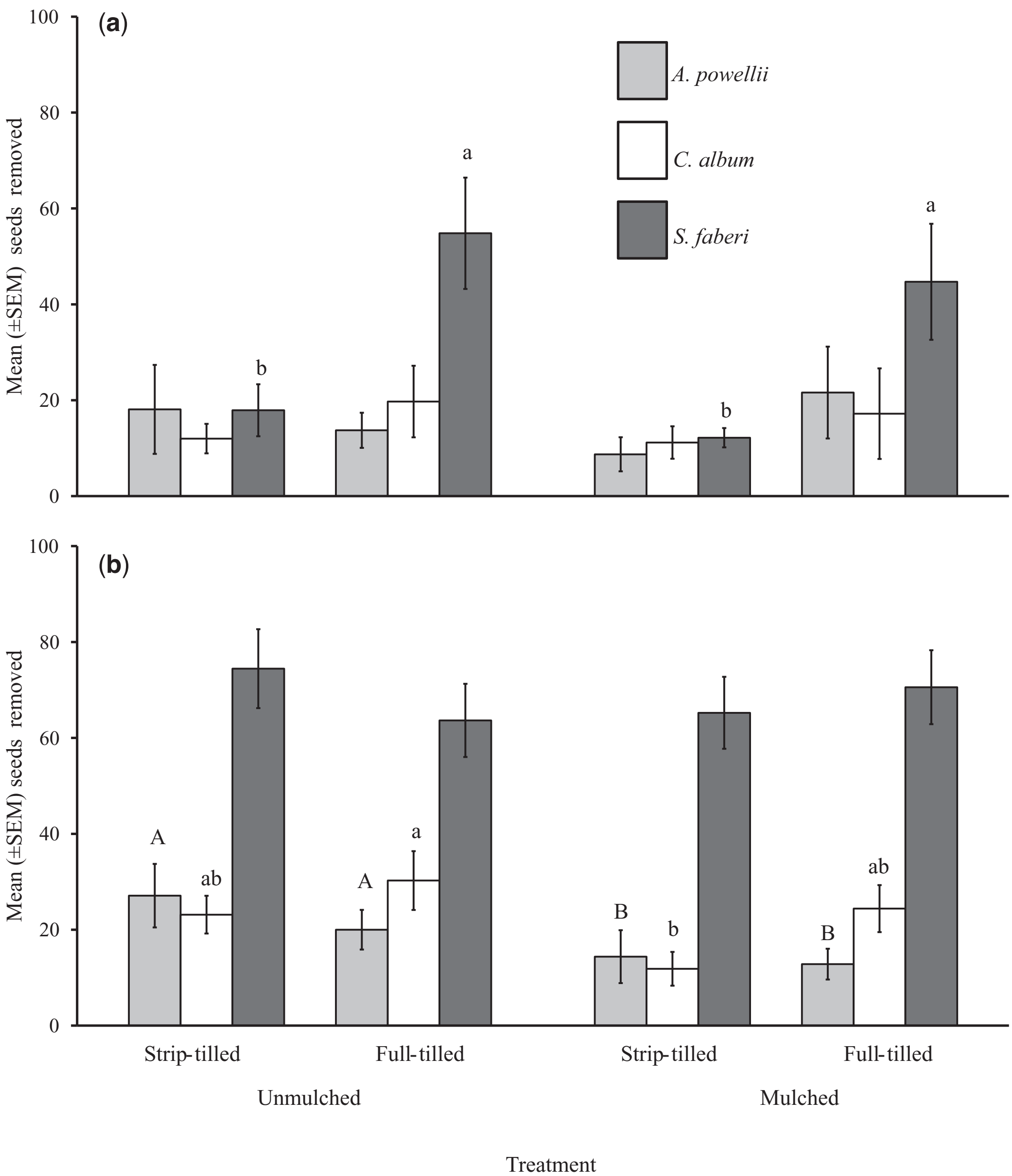

Fig. 3. Mean (±SEM) seed removal in 2014 (**a**) and 2015 (**b**). Arenas contained 100 seeds and were deployed for 48 h in plots that were strip-tilled or full-tilled, with no rye mulch added (unmulched) or 0.5 kg/m^2 rye mulch added (mulched). Significant differences within a weed species are indicated with different letters of the same case (Tukey's HSD, $\alpha = 0.05$).

which may have contributed to the lack of a statistically measurable response of arthropods on squash leaves to our treatments.

Contrary to our expectations, epigeal natural enemies of insects and weed seeds either did not respond to treatments or were typically more abundant in full-tilled plots and plots without mulch. Rates of seed predation aligned with this, with fewer seeds surviving in low complexity, high disturbance (full-tilled) plots in some cases. The reduction of insects found in pitfall traps in the presence of mulch residue could have been caused by insects moving shorter distances in the presence of vegetation in mulched treatments, essentially reducing their movement speed and reducing the likelihood of encountering the pitfall traps (Shearin et al. 2008). The mulch may have also increased alternative food sources for the natural enemies to utilize, such as rye seedheads or detritivorous insects, in turn reducing their overall movement and foraging activity. Although in our study the activity density appeared to be reduced in mulched areas, there is some evidence in the literature that cover cropping and mulch residues lead to higher abundances of ground beetles and other arthropods captured in pitfall traps (Shearin et al. 2008, Meiss et al. 2010, Ward et al. 2011, Blubaugh and Kaplan 2015).

The type of mulch or vegetation in cropping fields may also influence the activity density of some epigeal arthropods. For example, significantly more *Harpalus rufipes* (Coleoptera: Carabidae) were captured in pitfall traps in peat/oat-rye/vetch cover cropped plots compared to fallow and other types of cover crop plots (Shearin et al. 2008). Similar results were observed with another ground beetle (*Harpalus pensylvanicus*, Coleoptera: Carabidae), with higher activity densities in a mixed species plant treatment than single species plots (O'Rourke et al. 2006, Ward et al. 2011). Thus, combining cover crop species may improve the resources needed by some beneficial epigeal arthropods. We used a single species of cover crop, which may have contributed to the lack of a definitive positive response by ground beetles to cover crop mulch in our study. It is possible that the type of habitat created by the rye mulch did not provide the right resources for the arthropod assemblage that was found in our experimental fields.

Sufficient cover crop biomass is important for increasing the activity density of ground beetles (Ward et al. 2011). For example, peat/oat-rye/vetch cover crop plots had the highest cover crop biomass among several tested cover crop treatments and these plots also had the highest *H. rufipes* activity density (Shearin et al. 2008). Our results were likely influenced by the decomposition of the cover crop residues on the soil surface over time, contributing to the negligible difference among our mulch treatments during the weed seed predation trials. Although our current experiments did not investigate specifically the influence of vegetation biomass, future research should focus on the impact of cover crop mixes and different rates of mulch biomass on weed seed predators.

The frequency and timing of tillage during the growing season is another important factor that can impact epigeal predators. Our plots were tilled once at the beginning of the growing season and sample-dates closer to the date of tillage showed stronger tillage effect in our season-long assessment of ground beetle activity density in 2015. In contrast, frequent tillage for weed management during the entire growing season impacted *H. pensylvanicus* adult activity density with a 5-fold increase in plots with no tillage compared to tilled plots (Blubaugh and Kaplan 2015). Therefore, ground beetles, especially fall breeding species, may be relatively resilient to infrequent or early-season tillage events since we did not detect a reduction in their activity density in full-tilled plots compared to strip-tilled plots mid- and late-season. It is also possible that the beneficial effects of reducing or eliminating early-season tillage may take several years to manifest in the case of conservation biological control and weed seed predation. The findings of similar tillage and mulching studies have also been somewhat variable depending on the time frame of the experiment. Significantly more weed seed predators were found in no-till compared to full-till treatments in a long-term ecological study where tillage treatments were consistently applied to plots for about 10 yr prior to the weed seed predator experiments (Menalled et al. 2007). However, in another study where tillage treatments had only been implemented for 4 years, weed seed predator activity density was the same between no-till and full-till treatments (Cardina et al. 1996). In yet another example, after 15 years of tillage treatments, ground beetle activity density was the same across no-till and till treatments (van der Laat et al. 2015). This may indicate that in some instances yearly variation in abiotic and biotic factors might exert a greater influence on the insects than tillage. A combination of factors could have also contributed to the variability of results in our experiments: weed seed predators are habitat generalists with strong dispersing ability and our plots may have been too small to capture treatment effects.

Contrary to expectations, rates of weed seed removal were either unaffected or reduced by strip tillage and rye cover crop residue in our study (Ward et al. 2011, Blubaugh and Kaplan 2016). In particular, rates of removal of giant foxtail seeds were two to three times greater under full tillage than strip tillage in 2014. Similarly, in 2015, rates of removal of common lambsquarters were two to three times greater under full-tillage with no mulch, compared to strip tillage with a mulch. Although tillage is often cited as detrimental to seed predators and rates of seed predation (Brust and House 1988), several previous studies have also found reduced activity density of seed predators and lower rates of weed seed predation in no-till systems compared to tilled systems, suggesting that some important predators are well adapted to disturbance (Westerman et al. 2003a, Shearin et al. 2007).

Rates of seed predation and the activity densities of several granivorous species were not significantly correlated. Lower weed predation in mulched plots could have been caused by alternative food sources available in the form of the rye mulch seed heads in these treatments. Alternatively, tillage-induced differences in the number of ambient weed seeds near the soil surface adjacent to pitfall traps may have influenced predation rates in arenas. The direction of this effect is difficult to predict, since it depends critically on the initial distribution of weed seeds by depth. However, since our experimental site had a long history of conventional tillage, it is likely that weed seeds were initially relatively uniformly distributed by depth, and that tillage events used in this study did not dramatically alter the density of ambient seeds adjacent to our arenas. In both years, the number of Powell amaranth and common lambsquarters seeds recovered undamaged was numerically greater than the number of intact giant foxtail seeds recovered. In general, granivorous insects prefer smaller seeds, such as Powell amaranth and common lambsquarters, while vertebrates prefer to feed on larger seeds, such as giant foxtail (Honek et al. 2003, Westerman et al. 2003b, Pullaro et al. 2006, Honek et al. 2007). Others however have found that invertebrate seed predators can account for up to 90% of giant foxtail seed predation as measured by exclusion cages (Ward et al. 2011), and that crickets can consume 70–100% of giant foxtail seeds (O'Rourke et al. 2006). In our study, cricket activity density and giant foxtail seed predation was greater in strip-tilled plots but this pattern was not consistent. Thus, vertebrate seed predation may have played an important role in addition to invertebrate predation in our experimental plots.

In summary, our study demonstrated that tillage and mulch practices in vegetable cropping systems influence beneficial insects and rates of weed seed predation, but that these effects are inconsistent. The results suggest that early-season tillage may not be detrimental to epigeal predator assemblages and that it may take multiple years of practicing reduced tillage in a field for the ecosystem services to manifest. Future work will focus on the role of cover crop species and biomass on the abundance of beneficial arthropods in agriculture.

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