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Research

Biological Control - Parasitoids and Predators

# Ground beetles suppress slugs in corn and soybean under conservation agriculture

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Conservation agriculture practices such as eliminating tillage and planting high residue cover crops are becoming increasingly important in field crop systems in the US Mid-Atlantic. However, these practices have sometimes been associated with an increase in moderate to severe damage to field crops by slugs. Conserving natural enemy populations is a desirable way to manage slug infestations because remedial control measures are limited. Here, we tested the effects of conservation practices, weather, and natural enemies on slug activity-density measured by tile traps placed among 41 corn and soybean fields during the spring of 2018 and 2019 in the Northern Shenandoah Valley, Virginia, USA. We found that a positive effect of cover crops on slug activity-density was reduced by tillage and that slug activity-density declined with increasing ground beetle activity-density. Slug activity-density also declined with decreasing rainfall and increasing average temperature. Weather was the only significant predictor of ground beetle activity-density, which was reduced in sites and weeks that were relatively hot and dry or that were cool and wet. However, we also found a marginally significant negative effect of pre-plant insecticides on ground beetles. We suggest that the observed interacting effects of cover crops and tillage reflect favorable conditions for slugs provided by increased small grain crop residue that can be mitigated to some extent by even low levels of tillage. More broadly, our study suggests that implementation of practices known to promote recruitment of ground beetles in crop fields can improve natural suppression of slugs in corn and soybean that are being increasingly cultivated according to conservation agriculture practices.

*Key words:* conservation biological control, conservation agriculture, cover crop, gray garden slug, carabid beetles

## Introduction

Conservation agriculture practices are vital to sustainable agricultural production (Hobbs et al. 2008). Practices such as reduced- or no-tillage and planting of high-residue cover crops contribute to reducing soil erosion and runoff, improving soil organic matter and structure, and providing habitat for natural enemies, among other benefits (Derpsch 2008, Kremen and Miles 2012). In the last decade, conservation tillage was practiced on 65% of US corn acreage in 2016, and 70% of US soybean acreage in 2012 (Claassen et al. 2018), while US cover crop use increased by 50% (from 10.3 million to 15.4 million acres) between 2012 and 2017 (Wallander et al. 2021). Cover crops have become especially important in the US Mid-Atlantic (DE, MD, NJ, NY, PA, VA), where >15% of croplands had a cover crop in 2017, compared to the US average of <5% (USDA-NASS 2017).

Conservation agriculture practices are sometimes perceived to be at odds with early season pest management (Stinner and House 1990). This is especially the case for management of slugs in no-till corn and soybean, where slugs can thrive due to the moist and shielded environments provided by crop residues (Douglas and Tooker 2012). For instance, a survey of 41 farms in the Northern Shenandoah Valley region of Virginia found that 13% of no-till corn and soybean acres exhibited slug damage, while only 1% of conventional acres had slug damage (Clark 2013). However, slug damage also appeared to be related to insecticide use, with 65% of farmers who "always use insecticide" at planting reporting slug damage, compared to 13% of farmers who "never use insecticide" at planting, in line with research on effects of neonicotinoid seed treatments on insect predators of slugs (Douglas et al. 2015). Apparent effects of conservation agricultural practices on slug populations thus depend on multiple interacting abiotic and biotic factors (Le Gall and Tooker 2017).

Management of slug populations in no-till crops often relies on chemical molluscicides, typically applied in granular bait form, which are relatively expensive, less effective under the wet conditions that favor slugs, and toxic to wildlife (Rae et al. 2009, Lacey et al. 2015, Kumar 2020). Alternative management strategies include using row cleaners to remove crop residue directly above the seedbed to encourage faster crop germination and growth (Dively and Patton 2022), applying nitrogenous fertilizers at night with the dual purpose of acting as a slug contact poison (Dively and Patton 2022), and establishing the cash crop into a standing, green cover crop ('planting green') (Le Gall and Tooker 2017). This latter approach exploits slugs' foraging preference for certain cover crops while also favoring the recruitment of slug natural enemies within the crop field. Indeed, while there is no commercially available biological control agent for slugs in North America, there is an array of native and exotic predatory and parasitic natural enemies of slugs present (Barker 2004) that could be promoted through conservation agriculture practices.

In this study, using an observational dataset that measured early season slug (*Deroceras reticulatum* and *D. laeve*, Müller; Stylommatophora: Agriolimacidae) and natural enemy activity-density by deploying tile and pitfall traps across 41 corn and soybean fields in the Northern Shenandoah Valley, VA, in 2018 and 2019, we tested the effects of cover cropping, tillage, pre-plant insecticide use, weather, and natural enemies on slug activity-density. We separated natural enemies into 3 groups based on the predominant taxa observed, which comprised ground beetles (Coleoptera: Carabidae), harvestmen (Opiliones: Phalangiidae), and wolf spiders (Araneae: Lycosidae), and allowed for interacting effects on slug activity-density. We hypothesized that slug activity-density would be higher where there was more cover crop use, less tillage, more pre-plant insecticide use, wetter and cooler weather, and/or lower natural enemy activity-densities. Finding a significant effect of ground beetles on slug activity-density, we built a similar model to estimate the effects of the measured abiotic and biotic factors on ground beetle activity-density as well, hypothesizing that we would find positive effects of cover crops and negative effects of tillage and pre-plant insecticide use.

## Materials and Methods

### Field Sites

Slug and predatory arthropod sampling occurred in 2018 and 2019 in the Northern Shenandoah Valley region of Virginia, USA. We sampled a total of 41 commercial corn and soybean fields, 18 in 2018 and 23 in 2019 (Table 1, Fig. 1). Seven of the fields in 2018 were revisited in 2019. Of the 18 fields sampled in 2018, 9 were previously planted with cover crops (commonly barley, cereal rye, or wheat, and sometimes crimson clover or daikon radish) while 9 were not, 11 were no-till while 7 received reduced tillage (primarily vertical tillage), and 4 received a pre-plant insecticide (Table 1). Pre-plant insecticide refers to a pyrethroid application, sometimes tank-mixed with a pre-emergent herbicide (note that this is in addition to neonicotinoid seed treatments in corn). Of the 23 fields sampled in 2019, 9 were previously planted with cover crops while 14 were not, 13 were no-till while 10 received reduced tillage, and 8 received a pre-plant insecticide (Table 1).

### Slug Sampling

Slug sampling involved placing 4 30.5 $cm^2$ shingle traps, secured with a metal flag, along a linear diagonal transect within each field. Shingle traps remained in the field for 48 h before visual observations between daylight and 10:00 AM. Visual observations included flipping the shingle trap, searching below them, and moving residue to check for slugs for 2 min. Visual observations were also made by placing 4 30.5 $cm^2$ quadrats (open wooden frames) along another linear diagonal transect in each field and searching for slugs on the soil surface and under residue for 2 min. Slug adults and juveniles were counted, and counts were aggregated from shingle traps and quadrats to calculate the total number of slugs per 0.74 $m^2$ in a given field and sampling date. Slug sampling took place on 5 sampling dates between April 19 and June 15 in 2018 and on 6 sampling dates between 17 April and 28 June in 2019.

### Predatory Arthropod Sampling

Predatory arthropods were sampled from the same fields where slug sampling occurred. Predatory arthropod sampling involved placing 4 pitfall traps along a linear diagonal transect within each field. The pitfall setup included placing 2 nested 473-ml clear polypropylene containers (Fabri-Kal Corporation, Kalamazoo, MI) in the soil and filling them with 5 cm of glycol. Paper plates secured with wooden stakes were placed 4 cm above the pitfall trap to protect the traps from rainfall and debris (Fig. 2). Traps were removed after 48 h, and the arthropods collected and stored in 70% ethanol until identification. We focused identification and counting on 3 taxa: ground beetles, harvestmen, and wolf spiders. We identified ground beetles and wolf spiders to genus level, and harvestmen to species level because only 1 species was found (*Phalangium opilio*). Voucher specimens were preserved and submitted to Virginia Tech Insect Collection in Blacksburg, Virginia, and the Florida State Collection of Arthropods, Gainesville, FL.

### Weather Covariates

We curated weather data from each field and sampling date using daily climate summaries available from PRISM Climate Group (Prism Climate Group 2022). For each week prior to a sampling event, we summarized the number of days that had rain (>0 mm precipitation) and the average temperature within a 1 km radius of the sampled field. Weather data were curated using functions available in the "raster," "rgdal," and "rgeos" packages in the R computing software (Bivand and Rundel 2021, Bivand et al. 2022, R Core Team 2022, Hijmans et al. 2022).

### Data Analysis

We modeled slug activity-density (aggregated across shingle traps and frames) as a function of year, a 3-way interaction between tillage, cover crop planting, and pre-plant insecticide use, an interaction between days with rain and average temperature, and a 3-way interaction between activity-densities of ground beetles, harvestmen, and wolf spiders, with a generalized linear mixed model using the "glmmTMB" R package (Brooks et al. 2017). The 3-way interactions were included to account for potential cases where a covariate effect depended on another, such as how intraguild predation might influence effects of 1 predator in the presence of others. Errors were

**Table 1.** Slug and predatory arthropod sampling site characteristics

| Field | Year | Crop | Tillage | Cover crop | Pre-plant insecticide |
|---|---|---|---|---|---|
| Field 1 | 2018 | Corn | Reduced | Cover | No |
| Field 2 | 2018 | Corn | Reduced | Cover | No |
| Field 3 | 2018 | Corn | Reduced | Cover | No |
| Field 4 | 2018 | Soybean | No till | Cover | Yes |
| Field 5 | 2018 | Corn | No till | Cover | No |
| Field 6 | 2018 | Corn | No till | Cover | No |
| Field 7 | 2018 | Corn | No till | No Cover | No |
| Field 8 | 2018 | Soybean | No till | No Cover | No |
| Field 9 | 2018 | Soybean | No till | Cover | No |
| Field 10 | 2018 | Corn | No till | No Cover | No |
| Field 11 | 2018 | Corn | No till | Cover | No |
| Field 12 | 2018 | Corn | No till | No Cover | No |
| Field 13 | 2018 | Corn | Reduced | No Cover | Yes |
| Field 14 | 2018 | Corn | Reduced | Cover | Yes |
| Field 15 | 2018 | Corn | Reduced | No Cover | Yes |
| Field 16 | 2018 | Corn | No till | No Cover | No |
| Field 17 | 2018 | Soybean | Reduced | No Cover | No |
| Field 18 | 2018 | Soybean | No till | No Cover | No |
| Field 19 | 2019 | Corn | Reduced | Cover | No |
| Field 20 | 2019 | Soybean | No till | No Cover | No |
| Field 21 | 2019 | Corn | No till | Cover | Yes |
| Field 22 | 2019 | Corn | No till | Cover | Yes |
| Field 23 | 2019 | Corn | No till | Cover | No |
| Field 24 | 2019 | Corn | Reduced | Cover | Yes |
| Field 25 | 2019 | Corn | No till | No Cover | Yes |
| Field 26 | 2019 | Corn | Reduced | Cover | Yes |
| Field 27 | 2019 | Corn | Reduced | No Cover | No |
| Field 28 | 2019 | Soybean | Reduced | No Cover | No |
| Field 29 | 2019 | Corn | Reduced | No Cover | No |
| Field 30 | 2019 | Corn | No till | No Cover | No |
| Field 31 | 2019 | Corn | Reduced | Cover | Yes |
| Field 32 | 2019 | Corn | No till | Cover | No |
| Field 33 | 2019 | Corn | No till | No Cover | No |
| Field 34 | 2019 | Corn | No till | No Cover | No |
| Field 10 | 2019 | Soybean | No till | No Cover | No |
| Field 11 | 2019 | Corn | No till | No Cover | No |
| Field 12 | 2019 | Soybean | No till | Cover | No |
| Field 14 | 2019 | Soybean | Reduced | No Cover | Yes |
| Field 15 | 2019 | Corn | Reduced | No Cover | Yes |
| Field 16 | 2019 | Corn | No till | No Cover | No |
| Field 18 | 2019 | Soybean | Reduced | No Cover | No |

modeled using a negative binomial distribution ("family=nbinom2"). Covariates for year (2018 or 2019), tillage (no-till or reduced-till), cover crop planting (yes or no), and pre-plant insecticide use (yes or no) were treated as categorical variables. Covariates for days with rain, average temperature, and activity-densities of ground beetles, harvestmen, and wolf spiders were z-score transformed (mean-centered and scaled by standard deviation). We also included random intercepts for sampling time nested within field. We checked for spatial autocorrelation in residuals using functions available in the 'DHARMa' R package (Hartig 2022), and found none. We also checked a model without interactions for multicollinearity among covariates using the "performance" R package (Lüdecke et al. 2021), and found none (all variance inflation factors < 2). Significant covariate effects were visualized using functions available in the "sjPlot" R package (Lüdecke 2021).

Because we found a significant effect of ground beetle activity-density on slug activity-density, we also modeled ground beetle activity-density in a separate model. This ground beetle model contained the same overall structure and set of covariates, except that a 3-way interaction between (z-score transformed) activity-densities of slugs, harvestmen, and wolf spiders was included. We found no evidence of spatial autocorrelation in residuals or multicollinearity among covariates in the ground beetle activity-density model.

## Results

A total of 1,323 slugs were collected between 2018 and 2019, comprising 3 species: *Deroceras laeve*, *Deroceras reticulatum*, and *Arion subfuscus*. The majority (76%) of the slugs were collected in 2019, with average (± standard error) aggregate slug activity-densities across sites of 3.3 ± 0.8 in 2018 and 7.8 ± 1.2 in 2019. Slugs were found at all but 1 of the 41 fields. Of these fields, 70% (28/40) exhibited slug activity already by the first sampling event (April 19 in 2018; April 17 in 2019), while 10% and 20% did not exhibit slug activity until the 2nd or 3rd sampling events (between 1 and 18 May), respectively. Slugs remained active until the later sampling dates (mid-June) in 70% of the sampled fields. Slugs generally had higher early-season activity densities in 2019, with average (± standard error) aggregate slug activity-densities during 1st sampling events of 2.0 ± 0.9 in 2018 and 7.1 ± 1.9 in 2019.

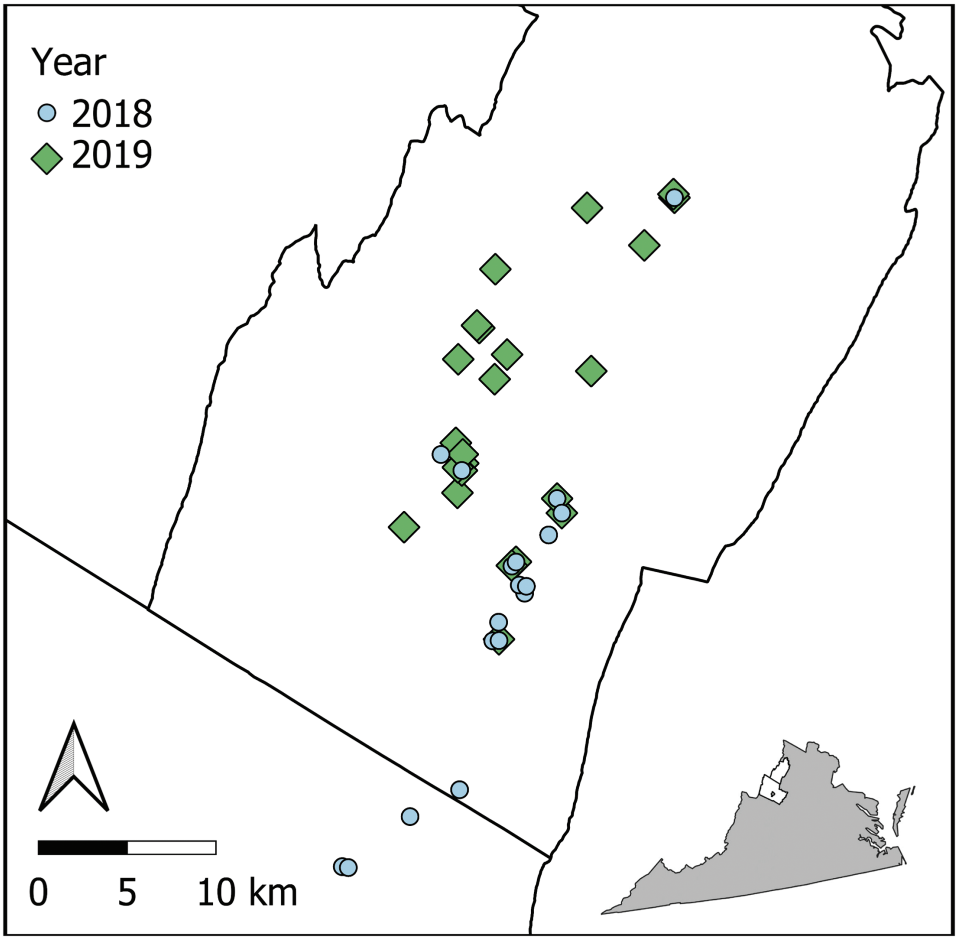


**Fig. 1.** Map of slug and predatory arthropod sampling field sites in the Northern Shenandoah Valley region of Virginia, USA. *N* = 41 (18 in 2018, 23 in 2019).

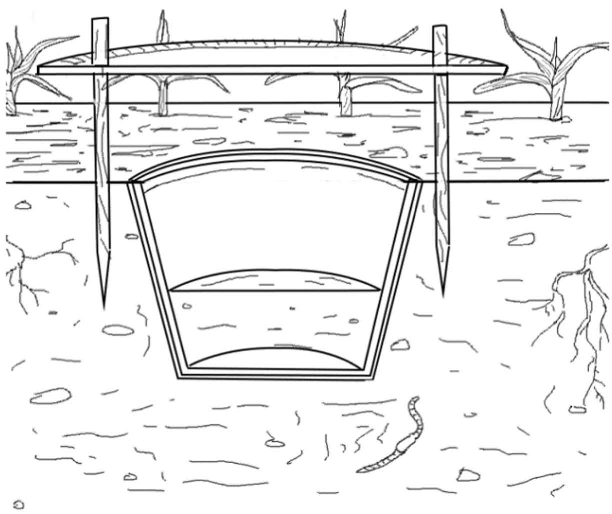

**Fig. 2.** Illustration of pitfall trap design used to sample predatory arthropods in the Northern Shenandoah Valley region of Virginia, USA, 2018–2019. Illustration by K. Brichler.

A total of 407 ground beetles, 963 harvestmen, and 779 wolf spiders were collected between 2018 and 2019. Ground beetle samples comprised 18 genera: *Acupalpus*, *Agonum*, *Amara*, *Anisodactylus*, *Altranus*, *Chlaenius*, *Cicindelidia*, *Dicaelus*, *Galerita*, *Harpalus*, *Notiophilus*, *Platynus*, *Poecilus*, *Pterostichus*, *Scarites*, *Selenophorus*, *Stenopholus*, and *Trichotichnus*. Only 1 harvestmen species, *Phalangium opilio*, was observed. Wolf spider samples comprised 13 genera: *Allocosa*, *Arctosa*, *Gladiocosa*, *Hesperocosa*, *Hogna*, *Pardosa*, *Pirata*, *Piratula*, *Rabidosa*, *Schizochosa*, *Tigrosa*, *Trochosa*, and *Varacosa*. Ground beetles were observed in all fields, and were typically observed as soon as the 1st (in 49% of fields) or 2nd (in 39% of fields) sampling date (between 19 April and 3 May). Harvestmen were observed in 78% (38/41) of fields, and were first observed on the 1st sampling date in 53% of these fields or on the 2nd sampling date in 19% of fields. Wolf spiders were observed in all 41 fields and were typically observed as soon as the 1st (in 78% of fields) or 2nd (in 7% of fields) sampling date. Ground beetle activity-density was on average 3 ± 0.5 in 2018, and 1.1 ± 0.2 in 2019. Harvestmen activity-density was on average 9.6 ± 1.9 in 2018, and 0.8 ± 0.2 in 2019. Wolf spider activity-density was on average 3.4 ± 0.4 in 2018, and 3.6 ± 0.7 in 2019. Ground beetles remained active until the later sampling dates (mid-June) in 47% of ground beetle-positive fields. Harvestmen remained active until mid-June in 59% of harvestmen-positive fields. Wolf spiders remained active until mid-June in 78% of wolf spider-positive fields.

The average number of days with rain among fields during the week of sampling was 4.7 ± 0.2 mm in 2018 and 3.5 ± 0.1 mm in 2019. The average temperature among fields during the week of sampling was 18.0 ± 0.5 °C in 2018 and 18.8 ± 0.3 °C in 2019.

Generalized linear mixed model analysis of aggregate slug activity-densities identified a significant interaction effect of tillage and cover crops (Table 2), wherein a positive effect of cover crops on slug activity-density in no-till fields was no longer apparent in reduced-till fields (Fig. 3A). Among activity-densities of arthropod predators considered, only that of ground beetles had a significant effect (Table 2). Slug activity-density decreased with increasing ground beetle activity-density (Fig. 3B). Main effects of days with rain and average temperature were also significant (but their interaction was not) (Table 2). Slug activity-density increased with increasing days with rain or decreasing average temperature (Fig. 3C and D).

Analysis of ground beetle activity-densities using a similar model identified only a significant interaction effect of days with rain and average temperature (Table 3). Ground beetle activity-density was higher in fields and sampling dates that were relatively wet and warm or dry and cool (Fig. 4). We also found a negative effect of pre-plant insecticide use, but this effect was only marginally statistically significant (Table 3).

## Discussion

Using observations across 41 corn and soybean fields over 2 yr in the Northern Shenandoah Valley region of Virginia, USA, we found important effects of conservation agriculture practices, ground beetle activity-densities, and weather on slug activity-densities. Notably, an apparent increase in slug activity-densities in cover cropped, no-till fields was apparently reversed by reduced-tillage (Fig. 3A). Slugs are generalists that benefit from the presence of living and decaying organic matter, and having a diversity of food sources allows them to optimize nutrient intake and growth (Le Gall and Tooker 2017). They prefer some cover crops over others, and the types of cover crops used in the Northern Shenandoah Valley region (small grains such as cereal rye and wheat) are known to be favorable for slug population growth (Le Gall and Tooker 2017, Rivers et al. 2018). So, finding a positive effect of cover crops in no-till fields was expected (though higher early-season plant cover can also promote slug predation; Rowen et al. 2022). It also makes sense that we found a reversal of this pattern in reduced-till, relative to no-till, fields. Tillage harms slugs by destroying favorable soil microclimates. The main reduced-till method used in our study region is vertical tillage or a very light disking. While this approach to tillage clearly does not result in the pervasive levels of disturbance seen in conventionally tilled fields, it could still modify soil microclimates sufficiently to suppress slug activity (e.g., Dively and Patton 2022). In contrast, we found no effect of cover crops or tillage on ground beetle activity-densities. This finding would also appear to run counter to other studies reporting important effects of cover crop residues (Hummel et al. 2002, Brevault et al. 2007, Blubaugh et al. 2016, Dunbar et al. 2017) and tillage (Kromp 1999, Hatten et al. 2007, Nash et al. 2008, Kosewska et al. 2014, Rowen et al. 2020) on ground beetle activity-density and community composition (though see for counterexamples: Quinn et al. 2016, Lewis et al. 2020, Rowen & Tooker 2021). However, our study did not include fields with the high level of disturbance (conventional tillage) considered by these previous studies, and ground beetle activity-densities may be less sensitive than slug activity-densities to the effects of reduced tillage. Furthermore, the influence of reduced tillage on ground beetle activity densities may be mitigated due to the hard-bodied and highly mobile characteristics of ground beetles (Lövei and Sunderland 1996, Kromp 1999)Ga'bor.

We observed a variety of predatory arthropods, including ground beetles, harvestmen, and wolf spiders in our study sites, but only activity-densities of ground beetles were significantly (negatively) associated with slug activity-densities (Table 2, Fig. 3B). Many ground beetle species are natural predators of slugs (Symondson 2004). Slugs are an important component of the diet of some ground beetles (Symondson et al. 2002), ground beetle activity-densities often cycle with slug activity-densities (Busch et al. 2020, Symondson et al. 2002), and ground beetles can reduce slug damage to crops in the laboratory (Oberholzer et al. 2003). So, the negative correlation that we observed between activity-densities of slugs and ground beetles could follow from some level of natural biological control provided by ground beetles in conservation tillage fields. However, this association could alternatively reflect differences in the conditions that favor slug versus ground beetle activity, as measures of ground beetle activity-densities using pitfall traps have been shown to be influenced by agronomic practices and weather conditions that

**Table 2.** Model estimates of covariate effects on aggregate slug activity-density. The 2.5% CI and 97.5% CI comprise the 95% confidence interval. Covariates whose 95% confidence intervals do not overlap zero are indicated by bold font

| Covariate | Estimate | Standard error | 2.5% CI | 97.5% CI |
|---|---|---|---|---|
| Intercept | −0.29 | 0.41 | −1.10 | 0.52 |
| Year (2019 vs 2018) | **2.10** | **0.36** | **1.40** | **2.80** |
| Tillage (Reduced- vs No-till) | −0.13 | 0.47 | −1.04 | 0.79 |
| Cover crop (Yes vs No) | **0.92** | **0.38** | **0.18** | **1.66** |
| Pre-plant insecticide (Yes vs No) | −1.37 | 1.03 | −3.39 | 0.64 |
| Days with rain | **0.51** | **0.16** | **0.19** | **0.83** |
| Average temperature | **−0.40** | **0.12** | **−0.63** | **−0.17** |
| Ground beetles | **−0.32** | **0.11** | **−0.54** | **−0.11** |
| Harvestmen | 0.05 | 0.22 | −0.38 | 0.48 |
| Wolf spiders | 0.13 | 0.11 | −0.09 | 0.35 |
| Tillage x Cover crop | **−1.79** | **0.88** | **−3.51** | **−0.06** |
| Tillage x Pre-plant insecticide | 1.37 | 1.22 | −1.02 | 3.77 |
| Cover crop x Pre-plant insecticide | 0.47 | 1.20 | −1.88 | 2.81 |
| Days with rain x Average temperature | 0.31 | 0.22 | −0.13 | 0.74 |
| Ground beetles x Harvestmen | −0.12 | 0.14 | −0.39 | 0.14 |
| Ground beetles x Wolf Spiders | 0.08 | 0.17 | −0.25 | 0.42 |
| Harvestmen x Wolf spiders | 0.13 | 0.22 | −0.30 | 0.57 |
| Tillage x Cover crop x Pre-plant insecticide | 1.20 | 1.60 | −1.93 | 4.34 |
| Ground beetles x Harvestmen x Wolf spiders | −0.48 | 0.25 | −0.97 | 0.01 |

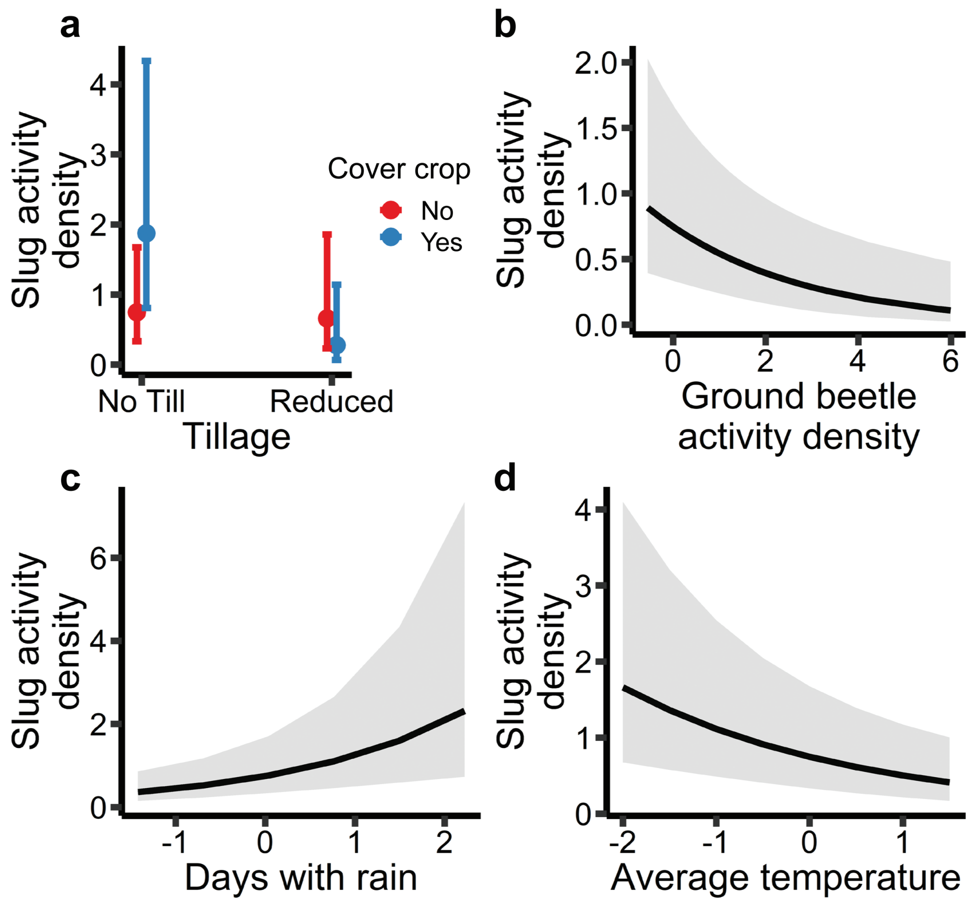


**Fig. 3.** Significant covariate effects on aggregate slug activity-density. Interaction effect of tillage and cover crops (a), effect of ground beetle activity-density (b), effect of number of days with rain during the week of sampling (c), and effect of average temperature during the week of sampling (d) on slug activity-density. Shaded area shows ±95% confidence intervals.

**Table 3.** Model estimates of covariate effects on ground beetles. The 2.5% CI and 97.5% CI comprise the 95% confidence interval. Covariates whose 95% confidence intervals do not overlap zero are indicated by bold font

| Covariate | Estimate | Standard error | 2.5% CI | 97.5% CI |
|---|---|---|---|---|
| Intercept | 0.11 | 0.43 | −0.73 | 0.95 |
| Year (2019 vs 2018) | 0.30 | 0.38 | −0.44 | 1.04 |
| Tillage (Reduced- vs No-till) | 0.06 | 0.33 | −0.59 | 0.72 |
| Cover crop (Yes vs No) | −0.17 | 0.33 | −0.83 | 0.49 |
| Pre-plant insecticide (Yes vs No) | −1.34 | 0.90 | −3.11 | 0.43 |
| Days with rain | −0.06 | 0.20 | −0.44 | 0.33 |
| **Average temperature** | **−0.38** | **0.15** | **−0.68** | **−0.08** |
| Slugs | −0.29 | 0.25 | −0.77 | 0.19 |
| Harvestmen | 0.49 | 0.32 | −0.13 | 1.11 |
| Wolf spiders | 0.17 | 0.15 | −0.12 | 0.46 |
| Tillage × Cover crop | −0.92 | 0.75 | −2.40 | 0.55 |
| Tillage × Pre-plant insecticide | 0.29 | 1.03 | −1.73 | 2.32 |
| Cover crop × Pre-plant insecticide | 1.47 | 1.00 | −0.49 | 3.43 |
| **Days with rain × Average temperature** | **0.58** | **0.25** | **0.08** | **1.07** |
| Slugs × Harvestmen | 0.15 | 0.63 | −1.07 | 1.38 |
| Slugs × Wolf Spiders | −0.22 | 0.17 | −0.56 | 0.12 |
| Harvestmen × Wolf spiders | 0.06 | 0.29 | −0.51 | 0.64 |
| Tillage × Cover crop × Pre-plant insecticide | 0.20 | 1.32 | −2.39 | 2.79 |
| Slugs × Harvestmen × Wolf spiders | 0.00 | 0.41 | −0.80 | 0.81 |

affect beetle activity apart from any differences in beetle abundance (Hatten et al. 2007). Likewise, pitfall traps may provide an imperfect measure of harvestmen and wolf spider activity-densities, potentially masking any effects of these arachnids on slugs (Rowen and Tooker 2021). As we did not collect data on crop damage or yield, our analysis ultimately cannot provide an explicit link between

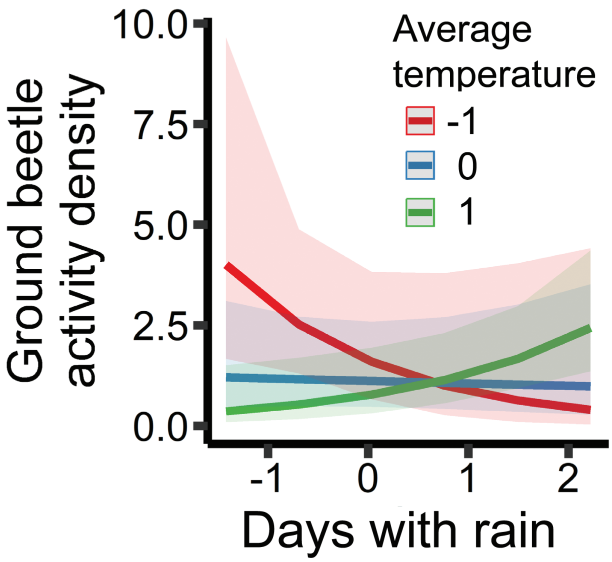


**Fig. 4.** Significant covariate effects on aggregate ground beetle activity-density. Shaded area shows ± 95% confidence intervals.

the activity-density of ground beetles or other predatory arthropods and crop protection.

Slug and ground beetle activity-densities were both associated with weather covariates. Weeks with lower average temperatures or with more frequent rainfall favored higher slug activity-densities (Fig. 3C and D), and this relationship was observed despite likely missing the earliest periods of slug activity. Slugs in the US Mid-Atlantic are known to be more active in the spring and fall when temperatures are relatively cooler (Douglas and Tooker 2012, Le Gall and Tooker 2017), and damaging outbreaks in corn and soybean often follow rain events (Douglas and Tooker 2012). We found evidence of an interaction effect of temperature and rainfall on ground beetle activity-densities, which were higher when conditions were relatively warm and wet or relatively cool and dry (Fig. 4). Ground beetles as a group represent a broad diversity of life histories and habitat preferences. As we did not identify beetles to species, we can only speculate as to why ground beetle activity-densities generally followed this pattern. Given the short time frame of the study, we interpret differences in activity-density to follow from changes in beetle activity, rather than from week-to-week changes in beetle abundance. For example, hygrophilic species such as *Agonum marginatum*, *Agonum muelleri*, *Anisodactylus binotatus*, *Chlaenius nigricornis*, and *Stenolophus mixtus* might be more active following rainfall than xerophilic species such as *Acupalpus meridianus*, *Amara aenea*, *Amara aulica*, *Harpalus affinis*, *Harpalus rufipes*, and *Poecilus cupreus* (Lambeets et al. 2008, Lessel et al. 2011, Nanni et al. 2019). Though not identical to weather effects on slugs, these results generally suggest that ground beetles in our study area can broadly remain active under similar weather conditions that typically favor slugs.

Conservation agriculture carries numerous benefits for soil health, but the effects on pest management are complex (Hatten et al. 2007, Alyokhin et al. 2020, Busch et al. 2020). Recent shifts toward cover crop planting and no-till, particularly in the US Mid-Atlantic primarily to protect sensitive watersheds, have raised concerns about management of early season pests like slugs (Busch et al. 2020). Cool, wet conditions often trigger damaging slug outbreaks that are difficult to suppress with chemical rescue treatments, and tillage as a control tactic is not an option for farms committed to no-till (Rowen et al. 2020). Given these limitations, there is great interest in implementing ecologically based pest management approaches. One such approach is "planting green," wherein the cash crop is planted into a living cover crop which is later terminated to make room for cash crop growth (Le Gall and Tooker 2017). This approach, when combined with abstaining from pre-plant insecticide use, has shown promise in reducing slug densities through a combination of drawing slug feeding away from the cash crop and increasing recruitment of ground beetles (Le Gall et al. 2022). Our finding of a marginally statistically significant negative effect of pre-plant insecticide use on ground beetle activity-densities is consistent with studies documenting the incompatibility of insecticidal seed treatments with ecologically based pest management (Disque et al. 2019, Douglas et al. 2015, Douglas and Tooker 2016, Dubey et al. 2020). Our finding of higher slug activity-densities in no-till, cover cropped fields, in contrast, would appear to conflict with planting green recommendations. However, effects of cover crops on activity-densities of epigeal predatory arthropods can depend on cover crop species composition and timing of cover crop termination (Rivers et al. 2018). For example, terminating a cover crop too soon before crop planting or germination can cause slug populations to increase and cause greater damage to the cash crop (Le Gall and Tooker 2017). This, combined with planting of cover crops whose decaying residues feed slugs (e.g., cereal rye and wheat; Le Gall and Tooker 2017, Le Gall et al. 2022), could explain the patterns that we observed, and suggests that our results neither support nor detract from findings of potential benefits to planting green. More broadly, our study suggests that implementation of practices known to promote recruitment of ground beetles in crop fields can improve natural suppression of slugs in corn and soybean that are being increasingly cultivated according to conservation agriculture practices.

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## Author Contributions

Thabu Mugala (Data curation-Equal, Formal analysis-Equal, Validation-Equal, Visualization-Equal, Writing – original draft-Equal, Writing – review & editing-Equal), Kirsten Brichler (Conceptualization-Equal, Data curation-Equal, Investigation-Equal, Methodology-Equal, Writing – review & editing-Equal), Bobby Clark (Resources-Equal, Writing – review & editing-Equal), Gareth S. Powell (Validation-Equal, Writing – review & editing-Equal), Sally Taylor (Conceptualization-Equal, Funding acquisition-Equal, Project administration-Equal, Resources-Equal, Supervision-Equal, Writing – review & editing-Equal), Michael Crossley (Data curation-Equal, Formal analysis-Equal, Software-Equal, Supervision-Equal, Writing – original draft-Equal, Writing – review & editing-Equal)

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