ABSTRACT

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| Title of Dissertation: | EVALUATING THE POTENTIAL BENEFITS AND SUSTAINABILITY OF A NOVEL LIVING AND DEAD COVER CROP MIXTURE IN MID-ATLANTIC CROP PRODUCTION |
| | Veronica Louise Johnson, Doctor of Philosophy, 2023 |
| Dissertation directed by: | Dr. Cerruti Hooks, Professor, Department of Entomology |

Modern vegetable production systems are often characterized by monoculture fields and the intensive use of tillage and/or synthetic agrochemicals for managing weeds and insect pests. A growing public interest in more sustainable and eco-friendly production practices has resulted in increased demand that crops be produced with lower inputs. Incorporating flowering living mulches and cover crop residues within crop fields can create an environment more hospitable to beneficial organisms and less conducive to pest outbreaks. My dissertation research aims to advance our knowledge in this area by evaluating the impacts of a novel cover cropping tactic which involves combining a perennial flowering living mulch with cover crop residue on insects and/or weeds. Further, it is often suggested that weed management requires a holistic approach; and that cover cropping will not be successful as a sole weed management tactic. As such, another research aim is to investigate whether combining a cover cropping tactic with herbicide sprays would result in better weed suppression and increased yield in sweet corn compared to using cover crops alone. An economic assessment was also performed to further evaluate the practicality of sweet corn producers adopting the management practices being investigated. Cost

of seeds, labor and other expenses can be a primary limitation to cover crop usage. To this point, I also evaluated the feasibility of using a single cover crop planting to suppress weeds over multiple cropping systems and field seasons. If a single cover crop planting can be used over multiple seasons, this could reduce the cost of cover crop use. Agricultural intensification and conversion of natural landscapes to crop production fields have contributed to declines in insect biodiversity including natural enemies and pollinators. Advancing our understanding of how increasing vegetational diversity within crop fields influences weed pressure and populations of herbivores and beneficial arthropods, as well as production costs, can facilitate the adoption of practices in annual cropping systems that favor beneficial organisms and conserves insect biodiversity.

# EVALUATING THE POTENTIAL BENEFITS AND SUSTAINABILITY OF A NOVEL LIVING AND DEAD COVER CROP MIXTURE IN MID-ATLANTIC CROP PRODUCTION

By

Veronica Johnson

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Professor Dr. Cerruti Hooks, Chair
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# Preface

This dissertation is composed in part of previously published work, included here as Chapter 1. Chapter 2 has also been submitted for publication and accepted pending minor revisions. The citations for these publications are as follows:

Johnson, V. L., A.W. Leslie, C.R.R. Hooks. 2023. Assessing the efficacy of living and dead cover crop mixtures for weed suppression in sweet corn. *Agronomy*. 13(3): 688

Johnson, V.L., A.W. Leslie, C.R.R. Hooks. 2023. Influence of cover cropping and conservation tillage on weeds during the critical period for weed control in soybean. *Weed Technology*. *Accepted pending minor revisions*

As directed in the graduate catalog, I state that I was responsible for the inception of the manuscript and the majority of manuscript preparation. Both publications were reformatted to meet university guidelines, but otherwise these publications have been exactly reproduced. They are cited as appropriate throughout the dissertation.

# Acknowledgements

This work would not have been completed without the assistance of numerous individuals. First, I would like to thank my advisor, Cerruti Hooks, for his continuous support and guidance throughout this entire process. I would also like to thank Galen Dively and Terry Patton for all the helpful guidance and fieldwork assistance they provided. Next, I thank Scott McCluen for his invaluable help identifying the many insects collected throughout this project, as well as Sam Droege for his assistance confirming the identity of all collected bee species. I also thank Shannon Dill for creating the enterprise budget necessary for the economic analysis. Finally, I thank my committee members Bill Phillips, Anahí Espíndola, and Kathryne Everts for the helpful feedback they provided as I developed these projects.

Many members of the Hooks Lab, particularly Rachel Lubitz and Matthew Dimock, have assisted with both field and laboratory work associated with my research over the years. This work also would not have been possible without the support of many undergraduate researchers, including Helen Craig, Alex Harris, David Lee, Eleanna Weissman, and Eirena Li. I would also like to than staff at the Beltsville and Upper Marlboro Research and Education Centers for their assistance in establishing and maintaining all experiment plots associated with this research. I would also like to thank Pam Biery, Josh Kiner, and Amy Yaich for providing considerable support managing the administrative side of my research. Finally, I would like to thank my family and my husband for all the love and support they have given me throughout the years.

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# Chapter 1: Assessing the Efficacy of Living and Dead Cover Crop Mixtures for Weed Suppression in Sweet Corn

**Abstract**

Modern vegetable production systems are often characterized by monoculture fields and the intensive use of tillage and/or synthetic agrochemicals for managing weeds. A growing public interest in more sustainable and eco-friendly production practices has resulted in increased demand for crops to be produced with more sustainable inputs. Field studies were conducted over three growing seasons to investigate the use of conservation tillage in concert with an interplanted living mulch and/or cover crop residue for managing weeds in sweet corn as compared with the standard practice of using conventional tillage and pre-emergence residual herbicides. Whole plot treatments included: (1) conventional till, (2) no-till with cover crop residue, (3) living mulch + cover crop residue, and (4) living mulch + winter killed residue. The split-plot factor consisted of herbicide treatments: (1) at-planting application of residual herbicides or (2) no herbicide. The cover crop systems suppressed weeds as well as the standard practice throughout the cropping cycle in all three years. In addition, there was no significant improvement in weed suppression with the application of herbicides within the cover crop treatments. Crop development and yield were similar among treatments in year 2. However, reduced yields were encountered in all cover crop treatments during year 3 relative to the conventional tillage treatment.

**Introduction**

Modern crop production systems are typically characterized by large monoculture fields and the intensive use of synthetic agrochemicals for managing weeds (Rüegg et al., 2007). This lack of diversity has resulted in undesirable side effects including the development of herbicide-resistant weeds, health-related issues resulting from occupational or consumer exposure to chemical residues, and increased farm expense. Integrated weed management programs designed to reduce chemical inputs often rely on mechanical weed control methods such as deep tillage and cultivation, as well as hand weeding. These tactics demand large amounts of fossil fuel or human labor and can therefore significantly increase production costs in conventional and organic farming systems (Archer et al., 2007; Sosnoskie & Culpepper, 2014). Furthermore, labor costs and shortages contribute to a need to reduce the amount of hand weeding, especially in organic operations (Taylor et al., 2012; Zahniser et al., 2018). An interest in more sustainable and eco-friendly production practices has resulted in a growing demand for crops to be produced with lower inputs (Rana & Paul, 2017).

In addition to the cost associated with intensive herbicide use, this tactic has several additional drawbacks. For example, there are a limited number of herbicides registered for use in vegetable crops, and many provide only partial weed control (Brainard et al., 2013). Furthermore, commonly used herbicides in vegetables may reduce yields by causing injury and stunting (Chen et al., 2018). Subsequently, many are not labeled for postemergence broadleaf weed control unless applied with shielded sprayers to prevent injury. Moreover, herbicide-resistant weed populations in many areas have resulted in the reduced efficacy of many commonly used herbicides (Kniss, 2018) and, due to the relatively small market size, chemical companies lack financial incentives to develop replacement products for many vegetable crops (Gast, 2008). These limitations suggest that additional weed management options are needed.

Increasing the number of available weed management options via the addition of cover crop residues and living mulches can help create cropping environments that are more diverse and less reliant on chemical inputs. Using conservation tillage practices together with cover cropping can reduce weed pressure and management cost through a reduction in hand weeding, herbicide sprays, and fuel usage (Mitchell et al., 2015). Cover crops suppress weeds, in part by filling ecological niches otherwise occupied by weeds. Moreover, different cover crop species, species combinations, and cover cropping tactics may result in varying levels of weed suppression. For example, cover crop residue that remains on the soil surface may suppress weed establishment by reducing the light levels needed for seed germination and by acting as a physical barrier to seedling germination and growth (Mirsky, Curran, Mortensen, et al., 2011). Furthermore, its efficacy may differ whether it is a grass or broadleaf cover crop (Teasdale & Mohler, 1993). Additionally, allelopathic compounds released by certain decomposing cover crops can hinder weed seed germination or act as plant growth inhibitors (Barnes & Putnam, 1986; Creamer et al., 1996; Ohno et al., 2000). Past research has highlighted the ability of surface residue created from fall-planted cover crops to reduce weed populations during the subsequent growing season (Kruidhof et al., 2008; Teasdale & Mohler, 2000). Furthermore, many studies have demonstrated greater weed suppression with increasing amounts of cover crop biomass (Florence et al., 2019; Mennan et al., 2020). Cover crop surface residues are typically created by terminating living cover crops using a roller-crimper, whereby rolling drums are fitted with dull blades designed to crimp stems rather than chop them.

Most research aimed at determining the impacts of conservation tillage and cover cropping on weed establishment was directed at agronomic crops. This has resulted in enhanced adoption of these practices in crops such as field corn and soybean (Wade et al., 2015). Previous attempts to incorporate cover crop residue and conservation tillage into vegetable production have often resulted in lower yields and/or delayed harvests caused by seedling interference and cooler soil temperatures (Hoyt, Greg, 1999). Furthermore, cover crop residues decompose over time and consequently may provide only early-season weed suppression. This can lead to weed establishment later in the season, particularly in the inter-row area where the soil surface is not covered by the main crop's canopy (Teasdale et al., 2007). Alternatively, cover crops used as living mulches and interplanted within the cash crop maintain the ability to suppress weeds throughout the cash crop cycle (Hartwig & Ammon, 2002). Nevertheless, living mulches are limited to suppressing weeds in the inter-row area, and if not properly managed, may compete with the main crop causing yield reductions (Mennan et al., 2020). Furthermore, the incorporation of living mulches into crop production may require banded herbicide sprays or strip tillage to clear out zones for establishing the crop rows. Strip tillage is a minimum tillage tactic that confines soil disturbance to a narrow zone within the crop row (Luna & Staben, 2002). However, soil disruption in the intra-row area may result in weeds emerging within the crop row. As such, weed management remains an important challenge in strip-tilled operations (Brainard et al., 2013; Lowry & Brainard, 2019). A potential method for eliminating the need for banded herbicides and strip tillage from living mulch crop production is to plant the living mulch in alternating strips with annual cover crops, such that the living mulch is restricted to the inter-row areas.

The purpose of this research was to investigate the use of conservation tillage in concert with an interplanted living mulch and/or cover crop residue for managing weeds in sweet corn and compare this with the standard practice of using conventional tillage and a pre-emergence herbicide application. Furthermore, we investigated the use of cover crop diculture systems, whereby alternating strips of living mulch and either a spring-terminated cover crop residue or frost-killed dying mulch were planted as a means of restricting the living mulch to the inter-row areas. We hypothesized that combining a living mulch with a terminated cover crop residue or frost-killed dying mulch would result in similar weed suppression compared to joint herbicides and tillage programs, and that both living mulch treatments would result in greater weed suppression than the no-till treatment by the end of the sweet corn growing season. Furthermore, we hypothesized that sweet corn productivity and yield would be similar among treatments.

## **Materials and Methods**

### ***Experimental Design and Field Operations***

Field operations were conducted in 2019, 2020, and 2021 at the Central Maryland Research and Education Center in Upper Marlboro, MD (38.859079°, −76.778731°, year 1), and roughly 16 km away in Beltsville, MD (39.011440°, −76.833356°, years 2 and 3). Soils at the study sites are Annapolis series (fine-loamy, glauconitic, mesic Typic Hapludults) (Upper Marlboro) and a Russett-Christiana complex where the Russett surface soil is classified as loam or sandy loam and the Christiana surface soil is classified as silt loam (Beltsville). Treatments were arranged in a Latin square split-plot design with four replicates. Whole plot treatments included: (1) conventional till (CT), (2) no-till with cover crop residue (NT), (3) living mulch + cover crop residue (LMRye), and (4) living mulch + winter killed residue (LMFR). The split-plot factor consisted of herbicide treatments: (1) an at-planting application of residual herbicides (herbicide) or (2) no herbicide application (no herbicide). Main plots measured 82.8 $m^2$ (9.1 m × 9.1 m) and each subplot measured 41.9 $m^2$ (4.6 m × 9.1 m).

During early fall, a mixture of crimson clover (*Trifolium incarnatum;* 3.36 kg $ha^{-1}$), forage radish (*Raphanus sativus*; 3.9 kg $ha^{-1}$), and cereal rye (*Secale cereale* L. 'Aroostook'; 62.8 kg $ha^{-1}$) was planted in CT and NT plots. In living mulch treatments, rows alternated between two rows of red clover (*Trifolium pratense*) and three rows of cereal rye (75.1 kg $ha^{-1}$) in LMRye or forage radish (11.2 kg $ha^{-1}$) in LMFR. Red clover was seeded at a rate of 9 kg $ha^{-1}$ in LMRye plots and 16.8 kg $ha^{-1}$ in LMFR plots. All cover crops were drilled at an interrow spacing of 15.2 cm. In the spring, when the rye reached anthesis, cover crops in CT plots were mowed, plowed, and incorporated into the soil. Crimson clover senesced naturally, and the forage radish was winter killed in 2019 and 2020. A roller crimper was used to terminate the rye in the NT and LMRye treatments, and temporarily slow red clover growth in LMRye and LMFR plots. In late May, sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) [variety: Providence (Syngenta, Wilmington, DE)] was seeded into each plot at an inter-row spacing of 76.2 cm, resulting in 12 crop rows per plot. In LMRye and LMFR plots, sweet corn seeds were planted within the center of the strips of forage radish or rye residue. A pre-emergence herbicide combination of 1.68 kg ai ha$^{-1}$ atrazine and 1.42 kg ai ha$^{-1}$ *S*-metolachlor was immediately applied to herbicide subplots following sweet corn planting. Herbicides were broadcasted in NT and CT herbicide subplots and banded within the strips (intra-row area) of the forage radish (LMFR) or rye (LMRye) herbicide subplots. Plots were overhead irrigated as needed to mitigate periods of low rainfall and a split-application of nitrogen fertilizer was applied according to recommended production practices. The timing of field tasks is provided in Table 1-1.

**Table 1-1.** Timing of field operations in 2019 (Upper Marlboro, MD), 2020, and 2021 (Beltsville, MD).

| Field Operation | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| Planted cover crops | 14 Sept 2018 | 5 Sept 2019 | 16 Sept 2020 |
| Terminated cover crops | 23 May 2019 | 25 May 2020 | 28 May 2021 |
| Planted + fertilized sweet corn | 23 May 2019 | 25 May 2020 | 1 June 2021 |
| Herbicide applied | 25 May 2019 | 27 May 2020 | 2 June 2021 |
| Fertilizer side dressed | 2 July 2019 | 24 June 2020 | 1 July 2021 |

***Cover Crop and Weed Biomass***

The cover crop and winter annual weed biomass were collected from each plot just prior to cover crop termination by clipping shoot tissue at the ground level from two 0.3 m × 0.3 m quadrats. Each quadrat was placed randomly in CT and NT plots and within the intra-row areas of the LMRye and LMFR treatments. Plant material within each quadrat was separated by a cover crop or weed, dried, and weighed. Biomass measurements of the red clover were not taken because the red clover remained a living mulch and continued to develop throughout the cropping cycle. However, it was noted that the red clover completely covered the soil surface in the inter-row areas.

To assess treatment impacts on weed biomass accumulation in the absence of any weed management intervention, two 0.78 $m^2$ unmanaged areas were established in each subplot immediately after sweet corn planting. Plot areas outside the unmanaged zones were manually weeded to assess the direct impact of cover crop competition on the yield. Biomass samples were collected from one unmanaged area six weeks after sweet corn planting (WAP) and the second immediately following the final sweet corn harvest. Measurements were taken by clipping and collecting all the weeds at the soil level. Weeds were separated by species, dried at 60 °C (>1 week), and weighed. Dry weight measurements were combined for each species to determine total biomass per treatment, and species measurements were used to calculate the relative abundances of the most common species.

***Crop Development and Yield***

Stand counts were initiated in all treatments at less than 10 d after planting. Counts were repeated every 3–4 d until all the viable seedlings had emerged. To assess the treatment impact on sweet corn growth, the developmental stage, extended leaf height, and chlorophyll content of five randomly selected plants per subplot were recorded. Measurements were taken weekly beginning at the V1 stage (the first leaf fully emerged) and continuing through VT (tassels fully visible). The corn development stage was determined according to (Ritchie et al., 1993). The extended leaf height was measured from the soil surface to the tallest extended leaf. Chlorophyll content was measured as an indicator of nitrogen level using a Soil Plant Analysis Development (SPAD)-502 chlorophyll meter (Spectrum Technologies Inc., Plainfield, IL, USA). Three measurements were taken per leaf (base, center, and leaf tip) from the last fully emerged leaf and averaged to provide a single value per plant. Chlorophyll meters were reported to detect nitrogen deficiencies by the V8 stage (Varvel et al., 1997). As such, the analysis of SPAD readings and crop growth parameters focused on those measurements taken between the V8 and VT stages. To estimate yield, all primary sweet corn ears located in the center 6.15 m of the four center rows within each subplot were harvested, and all marketable ears, or those with fully filled out tips, were counted and weighed. The yield was collected over multiple dates until all the marketable primary ears were harvested.

***Statistical Analysis***

Cover crop biomass was averaged within each treatment over all the experiment years and the standard error of the total biomass per treatment calculated. All plant growth and development metrics were analyzed using linear mixed models (LMM) to test for differences in emergence, crop chlorophyll content, extended leaf height, and development stage with treatment (CT, LMFR, LMRye, and NT), subplot treatment (herbicide vs. no herbicide), and their interaction as fixed effects. When the LMM indicated a significant difference between the treatment means, post-hoc pairwise means comparisons were performed using Tukey-adjusted *p*-values (Lenth, 2020). Similar analyses were performed on sweet corn yield and weed biomass data. Data were log transformed when necessary to stabilize the variances. For weed abundance, species that made up at least 5% of the total number of weeds (2019) or total biomass (2020, 2021) were listed. Data for all the experiment years were analyzed together unless a significant interaction between the year and cover crop treatment was detected. Seedling emergence and delays in harvest maturity were determined by calculating the proportion of the total emerged/harvested on each sample date. All statistical analyses were performed using R (v. 4.1.2; R Core Team 2021). Linear mixed effect models were built using the package 'lme4′ (Bates et al., 2015). Post-hoc means comparisons were performed using the package 'emmeans' (Lenth, 2020). All figures were made using the 'ggplot2′ package (Wickham, 2009).

## Results

### *Cover Crop and Weed Biomass*

Similar amounts of cover crop biomass were collected from each treatment each year; thus, the biomass of each cover crop species per treatment was averaged over all the study years. A high production of the cover crop biomass and comparatively low winter annual weed biomass occurred across all the treatments (Figure 1-1). CT biomass averaged 3891 kg ha$^{-1}$ and 2887 kg ha$^{-1}$ and NT biomass averaged 3926 kg ha$^{-1}$ and 2727 kg ha$^{-1}$ for rye and crimson clover, respectively. Rye biomass in LMRye averaged 7976 kg ha$^{-1}$ but was only planted in 60% of the plot area.

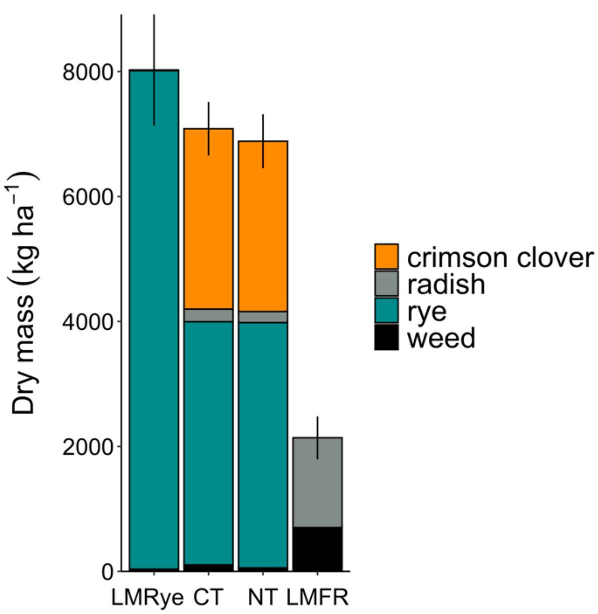


**Figure 1-1.** Mean biomass of cover crop and winter annual weeds collected immediately before termination averaged over all experiment years in plots designated as living mulch + rye

(LMRye), conventional tillage (CT), no-till (NT), and living mulch + forage radish (LMFR). Error bars denote the standard error of the mean.

The dominant weed species encountered six weeks after sweet corn planting across all the experiment years and locations were cutleaf evening-primrose (*Oenothera laciniata* Hill), goosegrass (*Eleusine indica* L.), and common lambsquarters (*Chenopodium album* L.). However, substantial variation in species abundance occurred between treatments. All weed species comprising >5% of the total biomass within each experiment year at 6 WAP are shown in Table 1-2.

**Table 1-2.** Percent of abundance of all weed species making up >5% total abundance.

| Common Name | Species Name | Treatment$^{-1}$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | CT (+) | CT (-) | NT (+) | NT (-) | LMFR (+) | LMFR (-) | LMRye (+) | LMRye (-) |
| 2019 | | | | | | | | | |
| Crabgrass, large | *Digitaria sanguinalis* (L.) Scop | 32.4 | 3.2 | 73.1 | 93.0 | - | 55.6 | 50 | 62.5 |
| Dandelion, common | *Taraxacum officinale* Weber | - | - | 9.0 | - | - | - | - | - |
| Goosegrass | *Eleusine indica* (L.) Gaertn. | 10.8 | 71.8 | 14.9 | 5.8 | 98.5 | 11.1 | - | 12.5 |
| Nutsedge, yellow | *Cyperus esculentus* L. | 48.6 | 24.7 | - | - | - | 33.3 | - | 25.0 |
| Plantain, narrowleaf | *Plantago, lanceolata* L. | - | - | - | - | - | - | 50 | - |
| 2020 | | | | | | | | | |
| Carpetweed | *Mollugo verticillata* L. | - | - | 6.2 | - | - | - | - | - |
| Crabgrass, large | *Digitaria sanguinalis* (L.) Scop | - | 14.5 | 25.1 | 79.7 | 5.4 | 31.9 | - | - |
| Evening-primrose, cutleaf | *Oenothera lanciniata* Hill | - | - | - | 5.4 | - | - | - | - |
| Goosegrass | *Eleusine indica* (L.) Gaertn. | - | 30.3 | - | 7.0 | 82.4 | 11.4 | 16.2 | - |
| Lambsquarters, common | *Chenopodium album* L. | 43.5 | 30.0 | - | - | - | - | - | - |
| Morningglory, ivyleaf | *Ipomea hederacea* Jacq. | 51.0 | 10.6 | 16.1 | - | - | - | 59.5 | - |
| Nightshade, eastern-black | *Solanum ptychanthum* Dun. | - | 6.0 | - | - | - | - | - | - |
| Nutsedge, yellow | *Cyperus esculentus* L. | - | - | 49.3 | - | - | 54.1 | - | 100.0 |
| Pigweed, redroot | *Amaranthus retroflexus* L. | - | 6.1 | - | - | - | - | - | - |
| 2021 | | | | | | | | | |
| Carpetweed | *Mollugo verticillata* L. | 35.7 | 33.8 | - | - | 35.7 | 5.4 | - | 7.1 |
| Crabgrass, large | *Digitaria sanguinalis* (L.) Scop | 40.4 | 21.4 | - | 88.2 | 37.9 | 2.6 | 100.0 | 9.7 |
| Evening-primrose, cutleaf | *Oenothera lanciniata* Hill | - | - | 95.2 | 7.0 | - | 53.0 | - | 77.9 |
| Goosegrass | *Eleusine indica* (L.) Gaertn. | - | 16.9 | - | - | - | - | - | - |
| Lambsquarters, common | *Chenopodium album* L. | 16.8 | 13.7 | - | - | - | - | - | - |
| Marestail | *Conzya canadensis* L. | - | - | - | - | - | 38.3 | - | - |
| Morningglory, ivyleaf | *Ipomea hederacea* Jacq. | - | - | - | - | 5.8 | - | - | - |
| Sida, prickly | *Sida spinosa* L. | - | 7.8 | - | - | 17.1 | - | - | 5.3 |

[1]CT = conventional till, NT = no-till, LMFR = living mulch + forage radish, LMRye = living mulch + rye residue, (+) denotes herbicide, and (-) denotes no herbicide subplot treatment.

No significant year effect was detected for the weed biomass measurements taken 6 WAP. As such, data from all the study years were combined and analyzed together. Significant treatment ($\chi^2$ = 11.32, df = 3, $p$ < 0.01), herbicide ($\chi^2$ = 33.93, df = 1, $p$ < 0.001), and treatment by herbicide interaction ($\chi^2$ = 11.86, df = 3, $p$ < 0.01) effects were found. Significantly greater weed biomass was collected in the no herbicide CT subplots compared to all the other whole-subplot treatment combinations except for NT no herbicide (Figure 1-2A). No differences were detected in the amount of weed biomass collected from herbicide and no herbicide subplots within each living mulch treatment (LMFR and LMRye) and amounts of weed biomass collected in all the cover crop subplots were similar to the herbicide-treated CT subplot. A significantly greater biomass was collected in the NT no herbicide subplot compared to the LMRye herbicide subplot. A significant effect of the study year was detected for biomass samples taken at crop harvest. However, $p$-value corrections resulting from Tukey pairwise comparisons did not detect any significant differences. Thus, study years were again combined for the analysis. Treatment effects on weed biomass at harvest were similar to those detected at 6 WAP. Significant treatment ($\chi^2$ = 16.60, df = 3, $p$ < 0.001), herbicide ($\chi^2$ = 15.95, df = 1, $p$ < 0.001), and interaction ($\chi^2$ = 13.11, df = 3, $p$ < 0.01) effects were found and the no herbicide CT treatment contained more weeds than all other subplot treatment combinations except for NT no herbicide (Figure 1-2B). No differences were detected in the amount of biomass collected from the herbicide and no herbicide subplots within each cover crop treatment and the amounts of weed biomass collected in all the cover crop subplots were similar to the herbicide-treated CT subplot.

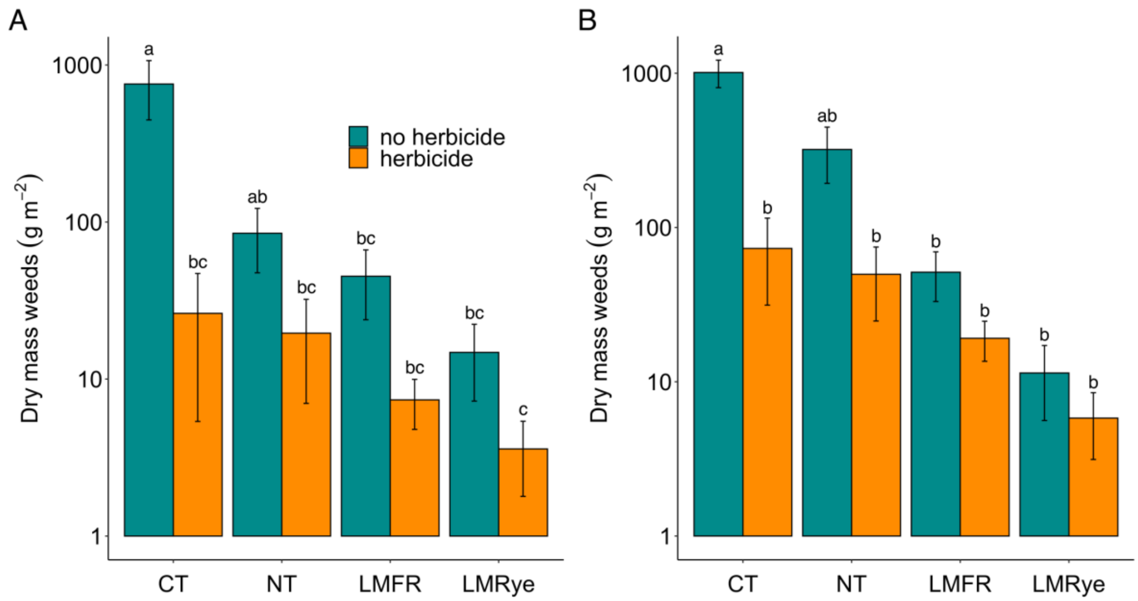


**Figure 1-2.** Weed biomass collected from unweeded areas **(A)** six weeks after sweet corn planting and **(B)** following crop harvest over three experimental years in conventional till (CT), no-till (NT), living mulch + forage radish (LMFR), and living mulch + rye residue (LMRye). Y axis presented on a log scale. Means bearing the same letter are not significantly different at the 5% probability level.

### *Crop Development and Yield*

Equipment used in 2019 caused poor seed placement and required replanting after initial establishment. Therefore, crop development and yield could not be measured in 2019 due to variations in overall crop maturity. In 2020, corn seedling emergence was roughly 1–2 days slower in NT and LMRye treatments compared to CT and LMFR (Figure 1-3A), while seedling emergence was approximately one day slower in LMRye compared to all the other treatments in 2021 (Figure 1-3B). In 2020, no significant treatment or herbicide differences were detected in the final stand count, leaf chlorophyll concentration, extended leaf height, crop development stage, or yield (Table 1-3).

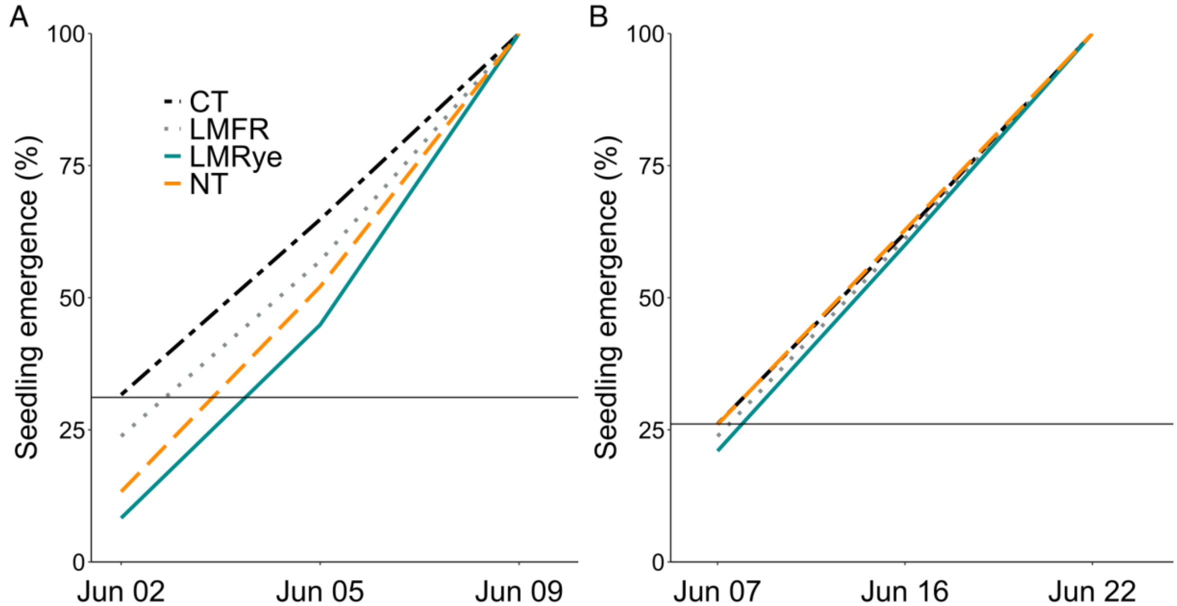


**Figure 1-3.** Percent of total sweet corn seedling emergence by sample date in **(A)** 2020 and **(B)** 2021 in conventional till (CT), no-till (NT), living mulch + forage radish (LMFR), and living mulch + rye residue (LMRye). Horizontal line marks the initial stand count in CT.

In 2021, no significant treatment or herbicide differences were detected in the final stand count. However, the average chlorophyll content differed by treatment ($\chi^2 = 15.06$, df = 3, $p < 0.01$) and herbicide ($\chi^2 = 12.00$, df = 1, $p < 0.001$). Lower chlorophyll levels were detected in no herbicide LMRye and LMFR compared to herbicide treated CT (Table 1-3). The extended leaf height differed by treatment ($\chi^2 = 14.73$, df = 3, $p < 0.01$) and herbicide ($\chi^2 = 26.68$, df = 1, $p < 0.001$) and an interaction effect was detected ($\chi^2 = 22.65$, df = 3, $p < 0.001$). Corn height was shorter in no herbicide subplots of NT, LMFR, and LMRye than their herbicide subplot equivalents and both CT subplot treatments. Similarly, in 2021, sweet corn stage differed according to treatment ($\chi^2 = 16.25$, df = 3, $p < 0.01$), herbicide ($\chi^2 = 27.03$, df = 1, $p < 0.001$), and their interaction ($\chi^2 = 38.72$, df = 3, $p < 0.001$). A developmental delay was detected in all the no herbicide cover crop treatments compared to their herbicide equivalents and both CT subplot treatments. In 2021, the total yield differed by treatment ($\chi^2 = 28.08$, df = 3, $p < 0.001$) and herbicide ($\chi^2 = 51.48$, df =

1, $p < 0.001$) and there was an interaction effect ($\chi^2 = 21.50$, df = 3, $p < 0.001$). The no herbicide cover crop subplots had lower yields than the no herbicide CT treatment (Table 1-3). Furthermore, all the no herbicide cover crop subplots experienced lower yields than their herbicide subplot equivalents. Although no differences in the total crop yield were detected in 2020, a harvest maturity delay of approximately one day in LMRye and two days in LMFR occurred compared to CT (Figure 1-4A). In 2021, a harvest maturity delay of approximately one day was detected in all the cover crop treatments compared to CT (Figure 1-4B).

**Table 1-3.** Mean ± SEM plant development and yield metrics for 2020 and 2021.

| Treatment [1] | Final Stand Count | Chlorophyll Content | Extended Leaf Height | Stage | Total Yield |
|---|---|---|---|---|---|
| | (Plants Row$^{-1}$) | (SPAD Units) | (cm) | (Expanded Leaves) | (1000 Ears ha$^{-1}$) |
| CT (+) | 31.38 ± 1.15 | 51.68 ± 0.83 | 120.18 ± 5.42 | 11.35 ± 0.33 | 36.33 ± 5.89 |
| CT (−) | 31.56 ± 1.40 | 51.05 ± 0.83 | 121.86 ± 4.93 | 11.30 ± 0.39 | 31.35 ± 5.94 |
| NT (+) | 27.60 ± 1.30 | 52.26 ± 0.64 | 108.01 ± 4.99 | 11.00 ± 0.29 | 30.27 ± 12.11 |
| NT (−) | 24.75 ± 1.56 | 51.67 ± 0.74 | 110.08 ± 4.58 | 11.00 ± 0.29 | 28.79 ± 4.13 |
| LMFR (+) | 32.38 ± 0.93 | 48.96 ± 1.04 | 120.08 ± 3.47 | 11.00 ± 0.26 | 40.77 ± 16.05 |
| LMFR (−) | 30.00 ± 1.19 | 49.01 ± 0.79 | 105.22 ± 4.33 | 10.75 ± 0.40 | 37.14 ± 2.21 |
| LMRye (+) | 27.75 ± 1.37 | 48.21 ± 1.24 | 133.18 ± 13.45 | 10.07 ± 0.45 | 33.73 ± 2.89 |
| LMRye (−) | 26.93 ± 1.15 | 46.51 ± 1.96 | 131.40 ± 13.16 | 9.60 ± 0.27 | 34.98 ± 3.06 |
| | | | 2021 | | |
| CT (+) | 33.38 ± 0.96 | 54.60 ± 1.31 a | 102.60 ± 3.57 a | 8.45 ± 0.25 a | 38.62 ± 1.54 a |
| CT (−) | 33.38 ± 0.49 | 51.28 ± 0.97 ab | 110.25 ± 3.60 a | 9.30 ± 0.27 a | 39.70 ± 3.04 a |
| NT (+) | 33.25 ± 0.73 | 49.04 ± 1.06 ab | 102.47 ± 3.51 a | 8.60 ± 0.20 a | 34.18 ± 3.06 a |
| NT (−) | 32.31 ± 0.72 | 45.51 ± 1.37 ab | 84.71 ± 4.57 b | 7.45 ± 0.28 b | 21.39 ± 3.97 bcd |
| LMFR (+) | 33.75 ± 0.66 | 49.01 ± 0.86 ab | 98.27 ± 4.62 a | 8.45 ± 0.33 a | 34.18 ± 3.76 ac |
| LMFR (−) | 34.31 ± 0.70 | 45.75 ± 1.54 b | 78.12 ± 4.40 b | 7.15 ± 0.22 b | 18.03 ± 4.62 bd |
| LMRye (+) | 32.43 ± 0.93 | 49.77 ± 1.37 ab | 90.74 ± 4.29 a | 7.85 ± 0.30 a | 25.03 ± 3.57 abc |
| LMRye (−) | 31.38 ± 1.05 | 44.78 ± 1.54 b | 68.21 ± 3.29 b | 6.00 ± 0.22 b | 8.75 ± 2.30 d |

[1]CT = conventional till, NT = no-till, LMFR = living mulch + forage radish, LMRye = living mulch + rye residue, (+) denotes herbicide, and (-) denotes no herbicide subplot treatment. Means bearing the same letter within columns and years are not significantly different at the 5% probability level. Missing letters indicate no significant difference. As a result of challenges associated with crop planting, 2019 development data was not included.

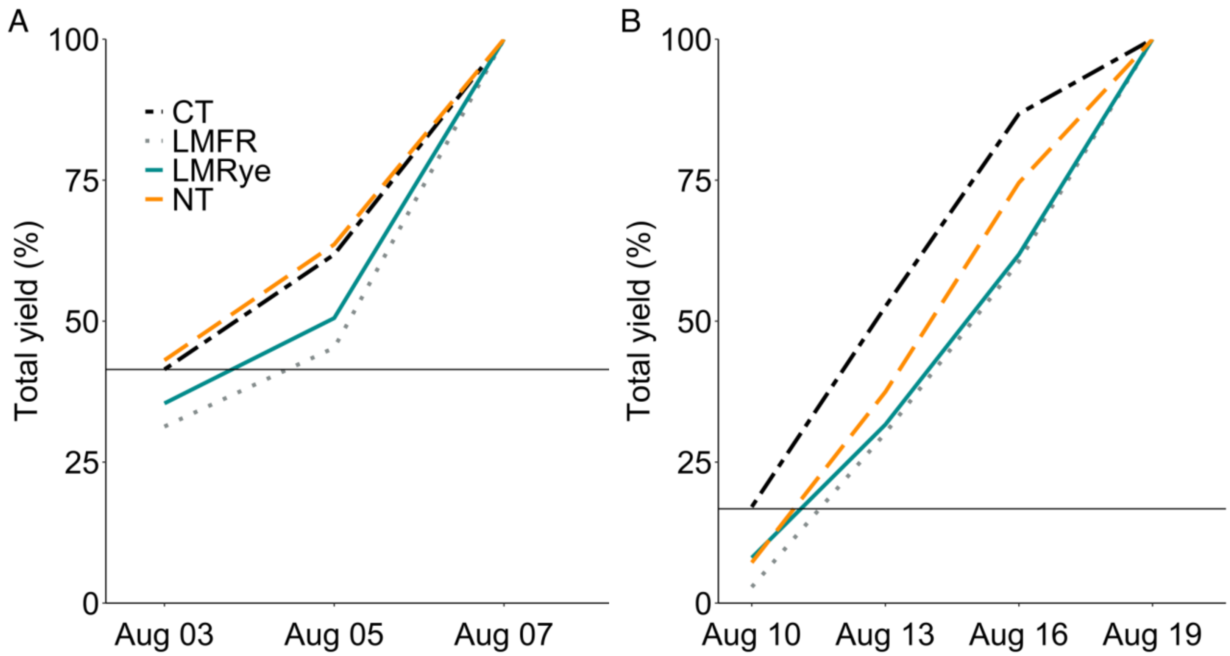


**Figure 1-4.** Percent of total sweet corn yield, measured as number of ears, harvested on each sample date in 2020 **(A)** and 2021 **(B)** in conventional till (CT), no-till (NT), living mulch + forage radish (LMFR), and living mulch + rye residue (LMRye). Horizontal line marks the initial yield in CT.

## Discussion

The high production of cover crop biomass and comparatively low winter annual weed biomass occurred across CT, NT, and LMRye treatments. Previous studies have associated high cover crop biomass with reduced weed biomass (Buchanan & Hooks, 2018; Mirsky, Curran, Mortensen, et al., 2011) and likely explains the low biomass of winter annual weeds observed in the CT, NT, and LMRye treatments across all the study years. Greater winter annual weed biomass was found in the intra-row areas of LMFR treatments, likely resulting from increased sunlight and warmer soil temperatures that occurred as forage radish residue decomposed.

Managing weeds in strip tillage vegetable systems can be challenging(Brainard et al., 2013; Lowry & Brainard, 2019). This is in p853: art due to differences in the weed communities typically found between the inter- and intra-row areas. Soil disturbance and reduced residue cover stimulate the germination of annual weeds in tilled zones(Froud-Williams et al., 1984; Teasdale et al., 1991; Wesson & Wareing, 1969), while untilled areas are more often plagued by a buildup of perennial weeds (Brainard et al., 2013). The cover cropping systems investigated during this study which involved combining a living mulch with a dying or killed organic mulch effectively suppressed weeds in the inter- and intra-row areas. As such, we determined that soil disturbances and subsequent weed flushes associated with strip tillage operations aimed to remove the living mulch from the intra-rows could be eliminated if the living mulch is restricted to the inter-rows and the intra-rows consist of organic mulch or decomposed cover crop residue. Our findings contrast previous research investigating the impact of interplanting sweet corn with strips of white clover (*Trifolium repens* L.) living mulch on weed establishment. Mohler (1991) found greater weed biomass in white clover treatments compared with sweet corn grown in rye residue or conventional tillage (Mohler, 1991). However, this finding was attributed to patchy white clover stands which allowed weed establishment. During the current study, it was also found that combining the living mulch treatments with an at-planting, pre-emergent herbicide application did not provide any additional weed suppressive benefits, except in NT treatments where the breakdown of residue allowed for late-season weed establishment in the absence of residual herbicides. Furthermore, combining rye residue with a living mulch resulted in significantly less weed biomass at crop harvest than the no-herbicide NT treatment and similar biomass to the NT herbicide subplot, suggesting that combining rye residue with a living mulch can provide similar late-season weed suppression to residual herbicides.

Variable treatment effects on sweet corn development and final yield were detected between experiment years. Previous research has found that lower soil temperatures under surface residues in minimum tillage systems can reduce or delay warm-season vegetable emergence and growth

(Hoyt, 1999; Kaspar & Erbach, 1998), and cooler soil temperatures can cause a delay in sweet corn seedling emergence (Garcia et al., 2009). However, treatment-specific emergence delays detected in 2020 and 2021 did not impact plant development metrics, chlorophyll content, or yield. Furthermore, no differences were detected in the final sweet corn stand counts during both study years. As such, growing sweet corn interplanted with a living mulch and/or within cover crop residue did not negatively affect crop establishment. The breakdown of winter-killed forage radish residues in LMFR treatments resulted in early-season bare-ground strips which allowed for warming of the soil prior to planting. As a result, unlike the NT and LMRye treatments, seedling emergence was not delayed in the LMFR treatment during 2020. Thus, the combination of living mulch with winter-killed cover crop residues presents a potentially compatible option for warm-season vegetables susceptible to temperature-induced development delays.

In 2021, sweet corn in no herbicide living mulch subplots contained reduced chlorophyll content compared to the herbicide-treated CT treatment. Measurements of leaf chlorophyll content using SPAD meters are a proven method for detecting nitrogen deficiencies in corn (Bullock & Anderson, 1998). Previous studies have shown that water shortages can reduce nitrogen uptake, thus resulting in reduced chlorophyll content, and that competition for water is an important mechanism by which living mulches may reduce crop yield (Hartwig & Ammon, 2002; Kurtz et al., 1952). Limited rainfall resulted in wilted, water-stressed plants in living mulch treatments during the early summer of 2021 before supplemental irrigation systems were established. As such, it is possible that reductions in sweet corn yield observed in living mulch subplots in 2021 resulted from either competition for water or nitrogen. This competition may have been alleviated if supplemental irrigation had been provided during the early sweet corn development stages. However, the system of irrigation used in this experiment did not allow for tractor entry into the plots, and therefore could not be established until after the final fertilizer application. In a prior study, competition for water with an interplanted white clover living mulch was also suggested as a factor contributing to reduced sweet corn yield (Mohler, 1991). Additionally, severe early-season stink bug damage in 2021 occurred primarily in NT, LMRye, and LMFR treatments. Previous research by Hardman et al. (2021) found that stink bug damage in seedling corn can cause reduced plant height and yield (Hardman et al., 2021). As such, the incurred stink bug damage likely contributed to a greater proportion of stunted sweet corn plants and lower yields in the cover crop compared to CT treatment in 2021.

Overall, interplanting sweet corn with a red clover living mulch and planting the corn rows into rolled rye or winter-killed forage radish residue resulted in the suppression of annual and perennial broadleaf and grass weeds in the inter- and intra-row areas throughout the cropping cycle. Furthermore, the weed suppressive effect was similar to the standard practice of tilling in the cover crop and applying a pre-emergent herbicide mixture at planting. This system can optimize the weed suppressive benefits of an interplanted living mulch while minimizing competition. Further, results from one experiment year indicate the potential to simultaneously maintain sweet corn yields. As such, the cover crop diculture systems researched here may be a viable option for diversifying integrated weed management programs in sweet corn and other vegetable plantings.

# Chapter 2: Influence of Cover Cropping and Conservation Tillage on Weeds During the Critical Period for Weed Control in Soybean

**Abstract**

Limited research has been directed at evaluating the ability of single cover crop plantings to suppress weeds in crops beyond the initial field season. Thus, this experiment was conducted to investigate the ability of a second-year self-seeded annual and second-year perennial cover crop planting to suppress weeds during the critical period for weed control (CPWC) in soybean (*Glycine max*). Whole plot treatments included: (1) conventional till, (2) no-till with cover crop residue, (3) living mulch + cover crop residue, and (4) living mulch + winter killed residue. Sub-plot treatments involved weed management intensity: a) no weed management (weedy), b) weeds manually removed through the CPWC (third node soybean stage; V3), and c) weeds manually removed until soybean canopy closure (weed-free). Overall, total annual cover crop biomass during the second field season was comparable to biomass obtained from direct seeded stands during the initial field season. All cover crop treatments reduced total weed biomass through the CPWC compared to conventional-till. Soybean yield was low across all treatments in this experiment. Still, yield was similar between cover crop and conventional till treatments at one site-year, however, yields were lower in all cover crop treatments at the other site-year.

**Introduction**

Cover crop residues and living mulches can suppress agricultural weeds (Creamer et al., 1996; Florence et al., 2019; Mirsky, Curran, Mortensen, et al., 2011), making cover cropping a viable practice in integrated weed management (IWM) programs. However, most cover crops need to be sown each year, and establishment costs are regarded as a primary economic issue that hinders their adoption (Duke et al., 2022; Dunn et al., 2016; Lemessa & Wakjira, 2015) and subsequent incorporation into an IWM plan. Recent policy initiatives, including the United States Department of Agriculture's Environmental Quality Incentives Program and the Risk Management Agency's Pandemic Cover Crop Program, have resulted in an increase in the number of farmers growing cover crops (Wallander et al., 2021). In 2017, U.S. farmers reported planting 6.2 million hectares of cover crops, a 50% increase compared to 2012, and in 2018, roughly one-third of the cover crop acreage planted was aided by financial assistance from federal, state, or other programs that foster cover crop adoption (Wallander et al., 2021). Still, adoption remains low, with cover crop use occurring on roughly 5% of the total cropped area in the U.S. (Deines et al., 2022). In addition to policy incentives, costs associated with cover crop planting may be mitigated by extending single cover crop plantings over several years. This can be accomplished by planting perennial or self-seeding annual cover crops. Cost savings from self-seeding annuals may help encourage their adoption (Bergtold et al., 2019). Additionally, time to plant cover crops following fall harvest is frequently stated as another barrier to adoption (Roesch-McNally et al. 2018). Self-seeding annuals or perennial cover crops would alleviate this concern. Further, if a single cover crop planting can contribute to weed suppression over multiple growing seasons, this will provide farmers an additional incentive for their adoption.

The CPWC is the duration of time during which weeds must be managed to prevent yield loss exceeding a defined threshold (Charles & Taylor, 2021). The CPWC contains two weed-crop competition components: the critical time for weed removal (CTWR) and the critical weed-free period (CWFP). The CTWR is the maximum length of time a crop can tolerate early season weed competition, and therefore determines the start of the CPWC. The critical weed-free period (CWFP) is the minimum length of time after planting when a crop must be kept weed free, thus determining the end of the CPWC (Knezevic et al. 2002; Rosset and Gulden 2019).

Recent research investigating the influence of cover crops on soybean [*Glycine max* (L.) Merr.] CPWC determined that the presence of a fall seeded cereal rye (*Secale cereale* L.) cover crop delayed the CTWR and shortened the CWFP, thus decreasing the CPWC (Kumari et al., 2023). Similarly, Price et al., (2018) found that the presence of a fall seeded cereal rye cover crop in combination with conservation tillage delayed the CTWR in cotton [*Gossypium hirsutum* L.] by approximately three weeks after planting, thus shortening the total CPWC. In addition to reducing weed biomass by hindering weed seedling emergence during the CWFP, cover crop residues and living mulches can slow the growth and development of seedlings that do successfully emerge through resource competition (Bhaskar et al., 2021). Several studies have investigated the use of conservation tillage and cover cropping for weed suppression in soybeans (Mirsky et al. 2011; Moore et al. 1994; Rosario-Lebron et al. 2019; Weber et al. 2017). However, limited research has been directed at determining how these practices impact weeds specifically during the CPWC. Yet, this information could assist growers in making more informed weed management decisions.

In soybeans, the CPWC extends until the third trifoliate stage or V3, which typically occurs roughly 30 days after planting (Van Acker et al. 1993). Weeds emerging after V3 are unlikely to have a significant impact on final grain yields. As a result, management is often considered beneficial beyond this stage only if weed presence will hinder harvest efficiency (Chandler et al., 2001). Notwithstanding, an important goal of IWM is preventing weeds from producing seeds, and subsequently increasing the weed seedbank and contributing to future weed problems (Haring & Flessner, 2018). Cover crop mulches may prevent weeds from reaching maturity through the harvest period by delaying weed emergence and slowing their development (Williams et al., 1998). This will consequently prevent viable weed seeds from entering the soil seedbank and reduce their impact in subsequent years (Walsh et al., 2013). Reducing weed seedbank entry is especially important when trying to thwart herbicide resistant weeds (Norsworthy et al., 2018) and reducing future weed problems, particularly in soybeans where weed interference is a limiting factor for successful soybean production (Stefanic et al., 2022). Additionally, soybeans can be relatively poor competitors compared to other field crops (Hammer et al., 2018). Cultural weed management practices, including the use of cover crops, if appropriately utilized as part of an IWM program can reduce herbicide usage, consequently lowering the selection pressure for herbicide resistant weeds (Bunchek et al., 2020).

Research has shown that some annual legumes such as crimson clover (*Trifolium incarnatum* L.) can be used as a cover crop for multiple seasons due to their ability to readily self-seed (Myers & Wagger, 1991; Rodrigues et al., 2015). Perennial cover crops may also be used for several production seasons (Sanders et al., 2017). However, limited research has been conducted to evaluate the ability of a single cover crop seeding event to suppress weeds beyond the initial field season. Thus, the purpose of this experiment was to investigate the ability of a second-year self-seeded annual and second-year perennial cover crop planting to suppress weeds through and beyond the CPWC in conservation tillage soybean. This experiment was part of a larger research project investigating the impact of conservation tillage and cover cropping on agricultural pests. For this experiment, it was hypothesized that the cover crop-conservation tillage systems would suppress weeds through the V3 soybean growth stage and that more weeds would reach their reproductive stages in the conventional than conservation tillage systems by the late soybean reproductive stage.

## Materials and Methods

### *Experimental Design and Field Operations*

Field experiments were conducted during two growing seasons at the Central Maryland Research and Education Center in Upper Marlboro, MD (38.859079°, -76.778731°; 2020) and Beltsville, MD (39.011440°, -76.833356°; 2021) within fields where sweet corn (var. Providence) was the test cash crop during the previous growing season. Average temperature was 21.3ºC and 22.3ºC, and total precipitation was 705mm and 678mm during 2020 and 2021, respectively. Soils at the experiment sites are Annapolis series (fine-loamy, glauconitic, mesic Typic Hapludults) (Upper Marlboro), and a Russett-Christiana complex where the Russett surface soil is a fine-loamy, mixed, semiactive, mesic Aquic Hapludults, and the Christiana surface soil is a fine, kaolinitic, mesic Aquic Hapludults (Beltsville).

Treatments were arranged in a Latin square – split plot design with four replicates. Whole plot treatments included: conventional till (CT), no-till with self-seeded cover crop residue (NT), second-year perennial living mulch + self-seeded forage radish (LMFR) residue and second-year perennial living mulch + self-seeded rye residue (LMRye). Each whole plot was subdivided into three subplots which received varying levels of weed management. Subplot treatments included weeds controlled: i) until the end of the CPWC for soybean (hereafter called V3), ii) until soybean canopy closure [weed-free (hereafter termed Wf)] and iii) no weed control [weedy (hereafter termed Wd)]. Main plots measured 82.8 $m^2$ (9.1 m × 9.1 m) and each subplot measured 23.6 $m^2$ (3.1 m × 9.1 m). Each subplot consisted of four soybean rows planted at an interrow spacing of 0.76 m. Weeds in V3 and WF subplots were removed weekly by hand pulling and hoeing. While manual weed removal is not the typical weed management practice for this crop, it was the most practical method for weed removal in this experiment.

All cover crops were drilled at an interrow spacing of 0.15 m. During early fall of 2018 (Upper Marlboro) and 2019 (Beltsville), crimson clover (3.36 kg $ha^{-1}$)*,* forage radish (*Raphanus sativus* 'longipinnatus'; 3.9 kg ha$^{-1}$), and cereal rye (*Secale cereale* L. 'Aroostook'*;* 62.8 kg ha$^{-1}$) were mixed and planted in CT and NT plots. Red clover (*Trifolium pratense* L.; 16.8 kg ha$^{-1}$) + forage radish (11.2 kg ha$^{-1}$) and red clover (9 kg ha$^{-1}$) + rye (75 kg ha$^{-1}$) were planted in alternating strips in the LMFR and LMRye plots, respectively. The alternating strips arrangement consisted of two rows of red clover followed by three rows of forage radish (LMFR) or rye (LMRye). After completion of a separate experiment investigating the impact of these cover crop treatments on weed suppression in sweet corn [*Zea mays* L.] (V. L. Johnson et al., 2023), all plots were flail mowed to eliminate the sweet corn stalks. Because cover crops in tilled plots were not expected to successfully reseed, the CT plots were also disked and the cover crop mixture of crimson clover, rye and forage radish were replanted at the same rates as the previous fall. Crimson clover and rye in the NT and LMRye treatments naturally self-seeded and the red clover in LMFR and LMRye remained established for the subsequent field season. Thus, the NT, LMFR and LMRye plots did not require any additional operations following flail mowing during the fall in preparation for the soybean experiment. Photos showing the arrangement of cover crops within all treatments are provided in Figure 2-1.

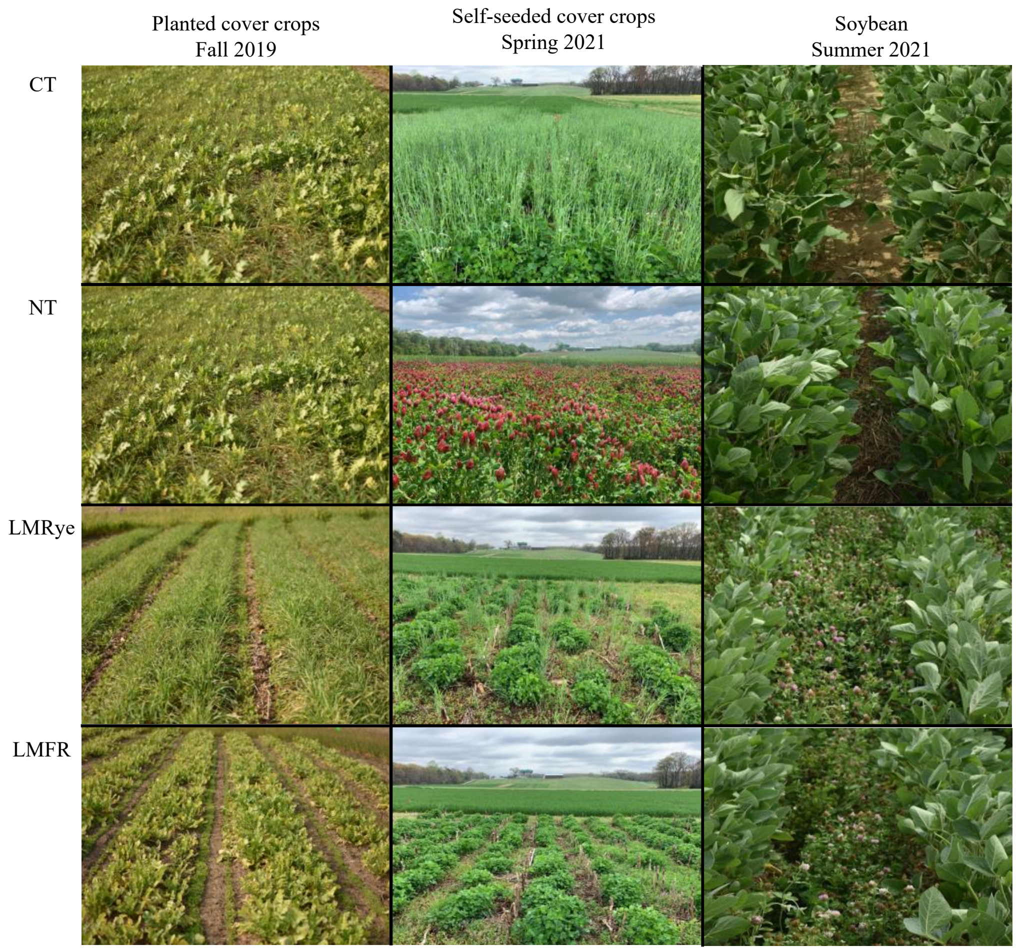


**Figure 2-1.** Images showing the cover crop arrangement in planted cover crops following emergence (Fall 2019) and self-seeded cover crops prior to termination (Spring 2021), as well as soybean arrangement (Summer 2021) at the Beltsville experiment site. CT = conventional till, NT = no till, LMFR = living mulch + forage radish, LMRye= living mulch + rye. In spring, CT treatments were flail mowed and tilled and NT, LMFR and LMRye treatments were roller crimped. LMFR and LMRye treatments were then strip tilled and soybean was planted into bare-ground in CT, rolled residue in NT, and tilled strips in LMFR and LMRye.

In the subsequent spring, when the rye reached anthesis, cover crops in CT plots were mowed and tilled to incorporate the cover crop residue into the soil (green manuring). A 3.0 m wide roller crimper was used to terminate the rye in NT and LMRye, and temporarily slow red clover growth in LMFR and LMRye. To clear encroaching living mulch from the intra-row areas, a two-row strip tiller equipped with cutting disks, a shank and rolling basket assembly (Bigham Brothers, Inc. Lubbock, TX) with a tillage width of 0.28 m was used in the LMFR and LMRye treatments.

In early June of 2020 and 2021, soybean (cultivar 'Monocacy') was seeded into each plot at an inter-row spacing of 0.76 m, resulting in 12 soybean rows per plot using a 3-point, 2 row vacuum planter (Monosem vacuum planter, Edwardsville, KS; 2020) and a no-till planter (John Deere 1750 MaxEmerge, Deere and Company, Moline, IL; 2021). Soybeans were seeded at a rate of 371,000 seeds/ha in 2020 and 383,000 seeds/ha in 2021. In LMFR and LMRye plots, soybean seeds were planted within the center of the tilled strips. In 2021, the grass herbicide fluazifop was applied as a rescue treatment at a rate of 0.84 kg ai $ha^{-1}$ to all Wf subplots to control a burgeoning population of grass weeds. Timing of field tasks is provided in Table 2-1. No supplemental irrigation was provided.

**Table 2-1.** Timing of field operations in Upper Marlboro, MD and Beltsville, MD.

| Activity | Upper Marlboro | Beltsville |
|---|---|---|
| Cover crops planted in all plots[1] | Sept 14, 2018 | Sept 5, 2019 |
| Cover crops replanted in CT[2] | Sept 3, 2019 | Sept 16, 2020 |
| Annual cover crops terminated | May 27, 2020 | May 28, 2021 |
| Soybean planted | May 27, 2020 | Jun 2, 2021 |
| Herbicide applied[3] | - | Jul 7, 2021 |
| Soybean harvested | Oct 28, 2020 | Oct 28, 2021 |

[1]Cover crops were initially planted in the prior field season for a separate field experiment;
[2]Cover crops used in soybean experiment had to be replanted in conventional till (CT) plots only;
[3]Rescue grass herbicide applied to weed free (Wf) subplots only.

### *Cover Crop and Winter Annual Weed Biomass*

Cover crop and winter annual weed biomass were collected from each plot just prior to cover crop termination by clipping shoot tissue at ground level from two 0.3 m × 0.3 m quadrats. Each quadrat was placed randomly in CT and NT and within one intra- and inter-row area of the LMFR and LMRye plots. Plant material collected within each quadrat was separated by cover crop or weed species, placed in paper bags, dried at 60ºC (>1 week) and weighed to determine dry biomass.

### *Weed Biomass, Species Assemblages and Maturity*

To assess treatment impact on weed emergence and biomass accumulation through the CPWC, weed biomass measurements were taken from Wd subplots at soybean stage V3 (third trifoliate). Two 0.3m x 0.3m quadrats were placed randomly in CT and NT and intra-row areas of LMFR and LMRye plots. Weeds were clipped at ground level and separated according to species. Quadrats were similarly used 2 weeks after canopy closure to measure weed biomass and estimate maturity stages of weeds within all subplots. The maturity stage was categorized as seedling, vegetative, bud, flower, immature seed, or mature seed. Determination of immature versus mature seeds was based on visual characteristics similar to those described by Hill et al., (2016). Samples collected at V3 were taken from the Wd subplots to provide a measurement of weed biomass accumulated through the CPWC in the absence of any weed management intervention. Samples collected two weeks after canopy closure were taken from all subplots. Dry weight measurements of each species were combined to calculate total weed biomass per treatment, and individual species measurements were used to compare species abundance between treatments.

***Soybean Emergence and Yield***

Soybean stand counts were initiated in all treatments less than 10 d after soybean planting. Counts were taken from the center two rows of each subplot and repeated every 3-4 d until all viable seedlings had emerged. To estimate yield, all soybean plants within the center 5.3 m of one interior row per subplot were manually harvested, threshed to separate the seeds from the pods, and all seeds were dried to 13% moisture and weighed.

***Statistical Analysis***

Biomass of each cover crop species was not analyzed statistically, but means and standard errors of each treatment were calculated for reference. Linear mixed models were performed on weed abundance, weed biomass, and soybean yield data to test for differences among the fixed effects of cover crop treatment (whole plot) and weeding intensity (subplot treatment). Plot identity was included as a random effect to account for the split-plot design. When there was a significant effect of cover crop treatment, pre-planned orthogonal contrasts were performed to test for treatment differences between: 1) CT and pooled cover crop treatments (NT, LMFR, and LMRye), 2) NT and pooled living mulch treatments (LMFR and LMRye), and 3) living mulch treatments (LMFR *vs.* LMRye). When there was a significant difference between subplot means, all pairwise comparisons were performed using Tukey-adjusted p-values (Lenth 2020). Weed biomass was log transformed to meet assumptions of normally distributed residuals. An alpha level of 0.05 was used throughout. All statistical analyses were performed using R (v. 4.1.2; R Core Team 2021). Linear models were built using the package 'lme4′ (Bates et al. 2015). Pre-planned contrasts and *post-hoc* means comparisons were performed using the package 'emmeans' (Lenth 2020). All figures were made using the 'ggplot2' package (Wickham 2009).

## **Results and Discussion**

### ***Cover Crop and Winter Annual Weed Biomass***

Spring biomass of fall-planted cover crops was similar between experimental sites. Likewise, total biomass of second-year self-seeded annual and second-year perennial cover crops was similar between sites (Table 2-2). In NT plots, the total biomass of the self-seeded cover crop measured in the spring of field season two was similar to the biomass collected during the spring of field season one from when the cover crop was directed seeded during the fall. However, the percent biomass of legume and grass cover crop in NT treatment differed markedly between the direct and self-seeded cover crops. In NT plots, the dry biomass of crimson clover was 2396 kg $ha^{-1}$ in Upper Marlboro and 4041 kg $ha^{-1}$ in Beltsville, and the dry biomass of rye was 4073 kg $ha^{-1}$ in Upper Marlboro and 2823 kg $ha^{-1}$ in Beltsville during the initial planting. However, following natural self-seeding, there was a markedly greater percentage of crimson clover in NT plots which was measured at 7043 kg $ha^{-1}$ in Upper Marlboro and 8812 kg $ha^{-1}$ in Beltsville. Contrastingly, in NT plots, rye biomass was imperceptible (0 kg $ha^{-1}$) at Upper Marlboro and measured at 54 kg $ha^{-1}$ in Beltsville (Table 2-2). Biomass measurements of red clover were not taken from LMRye or LMFR plots during the initial spring following cover crop planting (2019 in Upper Marlboro and 2020 in Beltsville). In these years, biomass data were only taken from the intra row area of these treatments, which consisted of rye or forage radish. The red clover was used as a living mulch as opposed to organic residue and was restricted to the inter-row area during the first field season following planting. However, by spring of the second growing season, the red clover extended into the intra-row area of LMFR and LMRye treatments. Strips of self-seeded cereal rye were mixed in with the red clover in the intra-row area of LMRye plots. However, self-seeded forage radish plants were not perceptible in any treatments during the second field season. Some winter annual weeds were present at low levels in all treatments during early spring (Table 2-2).

**Table 2-2.** Total spring biomass ± SEM of all cover crop species and winter annual weeds in kg $ha^{-1}$ in conventional-till (CT), no-till (NT), living mulch + forage radish (LMFR), and living mulch + rye (LMRye) treatment plots during the initial and subsequent field season.

| Treatment | Crimson Clover | Rye | Radish | Red Clover[1] | Total Cover Crop | Weed |
|---|---|---|---|---|---|---|
| | Upper Marlboro - original seeded cover crop during initial field season (2019) | | | | | |
| CT | 2967.6 ± 673 | 4342 ± 711 | 0 ± 0 | N/A | 7310 ± 662 | 42 ± 12 |
| NT | 2396 ± 699 | 4073 ± 332 | 0 ± 0 | N/A | 6470 ± 591 | 26 ± 10 |
| LMFR | N/A | N/A | 0 ± 0 | - | 0 ± 0 | 1020 ± 91 |
| LMRye | N/A | 7222 ± 364 | N/A | - | 7222 ± 634 | 34 ± 14 |
| | Upper Marlboro - self-seeded cover crop during subsequent field season (2020) | | | | | |
| CT | 2356 ± 1154 | 3311 ± 1120 | 0 ± 0 | N/A | 5736 ± 593 | 69 ± 31 |
| NT | 7043 ± 983 | 0 ± 0 | 0 ± 0 | N/A | 7049 ± 981 | 6 ± 6 |
| LMFR | N/A | N/A | 0 ± 0 | 3581 ± 1010 | 3816 ± 948 | 236± 104 |
| LMRye | N/A | 1071 ± 1037 | N/A | 1465 ± 470 | 3663 ± 612 | 126 ± 79 |
| | Beltsville - original seeded cover crop during initial field season (2020) | | | | | |
| CT | 2826 ± 1089 | 5534 ± 1204 | 391 ± 373 | N/A | 6571 ± 742 | 130 ± 117 |
| NT | 4041 ± 1111 | 2823 ± 866 | 221 ± 221 | N/A | 7085 ± 1097 | 91 ± 66 |
| LMFR | N/A | N/A | 1323 ± 668 | - | 1323 ± 668 | 513 ± 73 |
| LMRye | N/A | 6992 ± 2254 | N/A | - | 6993 ± 2254 | 75 ± 38 |
| | Beltsville - self-seeded cover crop during subsequent field season (2021) | | | | | |
| CT | 3732 ± 1235 | 4371 ± 888 | 82 ± 71 | N/A | 8184 ± 1215 | 82 ± 48 |
| NT | 8812 ± 1196 | 54 ± 41 | 0 ± 0 | N/A | 8866 ± 1203 | 74 ± 51 |
| LMFR | N/A | N/A | 0 ± 0 | 6098 ± 910 | 6098 ± 910 | 534 ± 222 |
| LMRye | N/A | 1449 ± 843 | N/A | 4767 ± 1326 | 6217 ± 1092 | 272 ± 132 |

[1]Red clover living mulch not sampled in LMFR and LMRye in spring following planting. All cover crops were initially planted in Upper Marlboro in Fall 2018 and in Beltsville in Fall 2019. Cover crops in CT treatment were replanted each year.

This experiment was designed, in part, to test the capacity for fall planted annual cover crops to naturally reestablish through self-seeding and a perennial cover crop to remain established the subsequent growing season. Overall, total cover crop biomass in plots with perennial and/or self-seeded cover crop was comparable to biomass obtained from direct seeded stands the prior cropping seasons. However, the proportion of individual species by weight changed in some treatments. For example, limited reseeding of cereal rye and forage radish in NT plots resulted in second year annual cover crop biomass that was predominantly crimson clover. This was expected as the rye was terminated prior to all plants reaching full anthesis and most of the forage radish winter killed while still vegetative. The red clover, which was mostly restricted to the inter-row areas in season one, overwintered and spread throughout the entire plot prior to the soybean planting date during season two. The high cover crop biomass across all treatments helped hinder winter annual weed establishment, resulting in low weed biomass at cover crop termination in all plots. The successful reseeding and overwintering of annual and continued growth of perennial cover crops may prove useful for growers who are unable to direct seed cover crops following fall harvest or desire to avoid the additional labor or cost associated with replanting, as well as farmers who prefer that their cover crops are established earlier in the growing season. Roesch-McNally et al., (2018) identified difficulty in timing of cover crop establishment as a specific challenge associated with cover crop usage. There is often insufficient time to establish a cover crop following late harvested crops such as corn and soybean (Roesch-Mcnally et al. 2018; Wallace et al. 2017). Further, if planted too late, this could result in insufficient biomass needed to suppress weed establishment during the subsequent cropping season (Akbari et al., 2019). Lawson et al. (2015) found that delaying the planting of winter cover crops by two to three weeks can have a marked effect on their ability to protect soil and produce biomass. More specifically they discovered that delaying their planting by 2.5 weeks reduced average winter ground cover by 65% and biomass by 50%. As such, using self-seeded annual or established perennial cover crops provides an additional cover cropping strategy that may ameliorate some of the issues associated with planting cover crops annually.

***Weed Biomass, Species Assemblages and Maturity***

In 2020, greater weed biomass was collected from Wd subplots at the end of the CPWC (31 days after soybean planting) in CT, in which cover crops were terminated in spring prior to tillage and soybean planting, compared to all cover crop treatments (LMFR, LMRye, and NT; $t_{12}$

= 12.65, $p < .0001$), and in NT compared to the living much treatments (LMFR and LMRye; $t_{12}$ = 8.86, $p < .0001$), and in LMFR compared to LMRye ($t_{12} = 2.00$, $p = .02$; Figure 2-2). In 2021, weed biomass was again greater in CT compared to the cover crop treatments ($t_{11} = 5.10$, $p = .03$). In contrast, weed biomass in NT was less than the living mulch treatments ($t_{11} = 3.64$, $p = .05$) and no difference was detected between LMFR and LMRye ($t_{11} = 0.01$, $p =$

.98) at the end of the CPWC (38 days after planting; Figure 2-2). Substantial variation in weed species abundance occurred between experiment site-years and treatments at the conclusion of the CPWC. Dominant species in 2020 in Upper Marlboro were primarily carpetweed (*Mollugo verticillata* L. 22%), white clover (*Trifolium repens* L. 31%) and goosegrass (*Eleusine indica* (L.) Gaertn. 33%). In 2021 in Beltsville, dominant weed species were yellow nutsedge (*Cyperus esculentus* L. 14%), goosegrass (15%), and giant foxtail (*Setaria faberii* R.A.W. Herrm. 37%).

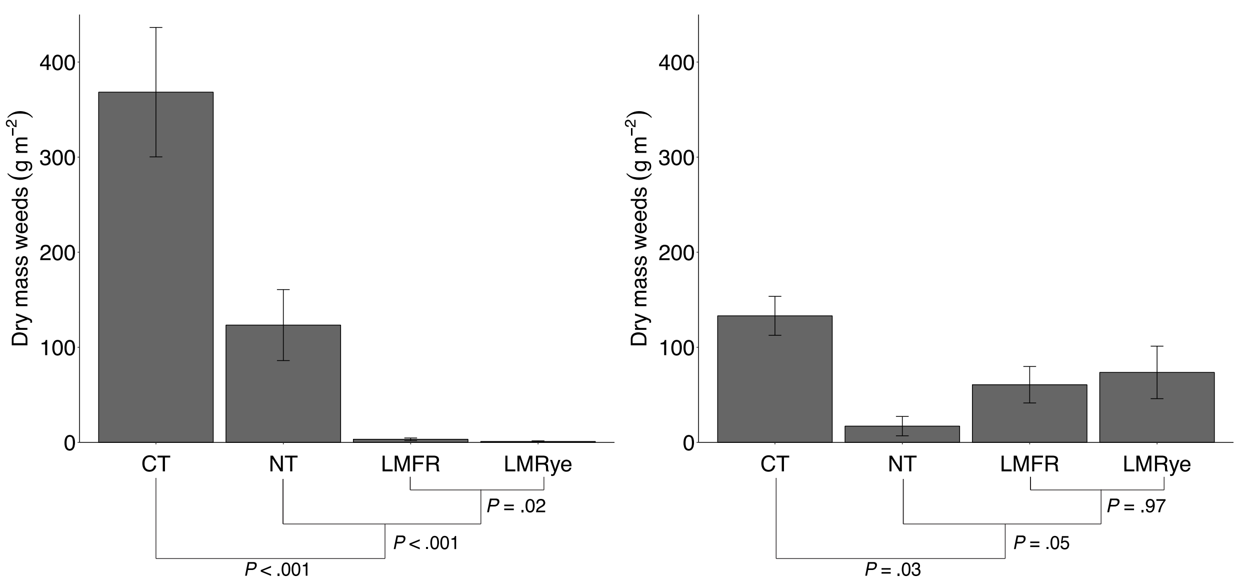


**Figure 2-2.** Dry mass of weeds ±SEM accumulated through V3 soybean stage in 2020 in Upper Marlboro, MD (left) and 2021 in Beltsville, MD (right) in conventional-till (CT), no-till (NT), living mulch + forage radish residue (LMFR), and living mulch + rye residue (LMRye). *P*-values represent significance levels for contrasts of groups intersecting at those nodes.

Several studies have investigated how various cultural practices, including cover cropping, impact the timing of the CPWC in soybeans (Halford et al. 2001; Kumari et al. 2023; Rosset and Gulden 2019) and other crops (Price et al. 2018; Tursun et al. 2016). However, no studies have specifically investigated the influence of cover crop residues or living mulches on weed growth and development during the CPWC. Relevant to this, a meta-analysis conducted by Osipitan et al., (2018) found that cover crop residues provided early-season weed suppression comparable to that provided by chemical and mechanical weed control methods. However, it is unclear whether this suppression occurred during the CPWC. During the current experiment, variable levels of weed suppression occurred among treatments and years through the V3 soybean stage. Still, all cover crop treatments consistently reduced weed biomass compared to the CT treatment. However, the NT treatment contained greater weed biomass compared to the living mulch treatments at the end of CPWC in 2020 and less weed biomass in 2021. In 2020, perennial white clover made up much of the weed biomass in the NT treatment, suggesting the cover crop residue could not adequately suppress white clover. Previous research has demonstrated that the weed-suppressive effects of cover crop residues are species specific and that perennial weed species are not adequately suppressed by cover crop residue (Liebman and Davis 2000; Mirsky et al. 2011, Mohler and Teasdale 1993). In contrast, low white clover biomass was found in LMFR and LMRye in 2020, suggesting a living mulch may be more successful in preventing some perennial weeds from establishing in crop fields than cover crop residue. Similarly, Hiltbrunner et al. (2007) found that living mulches were more effective in preventing the germination and establishment of perennial weeds than killed cover crop residues. Although treatment differences were detected between LMFR and LMRye during 2020 in Upper Marlboro, this difference may not be agronomically important in most production scenarios as weed levels remained low in both treatments. In 2021 in Beltsville, the red clover did not establish well, and open gaps were exploited by weeds which likely contributed to the greater weed biomass collected from living mulch than NT treatment. When using cover crop residue for weed suppression, the amount of biomass is critical (Nichols et al., 2020). However, for a clover living mulch, having the ground completely covered is presumably more important than the overall biomass as gaps in stand can be exploited by weeds (Basinger & Hill, 2021). Still, weed biomass was low across all treatments in Beltsville during 2021.

In Upper Marlboro during 2020, weed maturity measurements were not taken as soybean plants matured much later than anticipated. As such, it was noted at the time of soybean harvest that weeds in all treatments had senesced. In the data presented here, all weed maturity results pertain to Beltsville in 2021. Variation in species abundance between treatments and subplots precluded the ability to conduct maturity comparisons among treatments for individual species. As such, all weed species were pooled for comparisons. Overall, a greater amount of reproductive stage weeds (flower, immature seed, and mature seed) were present 2 weeks after soybean canopy closure in Wd compared to V3 or WF subplots ($\chi^2$ = 90.33, df = 1, $P$ < .001; Table 2-3). No treatment differences were detected within any subplots. Reproductive stage weeds were present in low numbers at V3 in CT, NT and LMRye subplots, and their total biomass was not significantly different from zero. WF subplot treatments did not contain any reproductive stage weeds and were therefore not included in the analysis (Table 2-3). These findings contrast our original supposition that more reproductive stage annual weeds would be present in CT than conservation tillage cover crop treatments. It was expected that the cover crops would provide an additional source of competition, resulting in reduced weed emergence and delayed weed maturation compared to the bare-ground CT treatment. However, in 2021, the red clover in the LMFR and LMRye plots was patchy which allowed open areas for early weed establishment, notably grass species.

The low biomass of reproductive stage weeds in V3 subplots suggests that restricting weed management to only to the CPWC period is sufficient in some production situations. However, if highly prolific weed species are present, even low numbers of reproductive stage weeds can result in large numbers of unwanted seeds entering the seedbank (Schwartz et al., 2016). Further, if herbicide resistant weeds are present, low numbers of these seeds entering the seedbank is undesirable.

**Table 2-3.** Total biomass ± SEM of weed species in reproductive stages 2 weeks following soybean canopy closure in 2021 in Beltsville, MD.

| | Weed biomass | | |
|---|---|---|---|
| Treatment[1] | Wd | V3 | Wf |
| | ----------------- $g\ m^{-2}$ ----------------- | | |
| CT | 92.5 ± 36.9 | 2.3 ± 1.5 | 0.0 ± 0.0 |
| NT | 19.5 ± 10.0 | 3.7 ± 2.6 | 0.0 ± 0.0 |
| LMFR | 50.7 ± 29.1 | 0.0 ± 0.0 | 0.0 ± 0.0 |
| LMRye | 49.8 ± 27.0 | 0.9 ± 0.4 | 0.0 ± 0.0 |

[1]CT = conventional till, NT = no till, LMFR = living mulch + forage radish, LMRye= living mulch + rye; Wd = unweeded, V3 = weeds controlled through soybean CPWC (V3 stage), Wf = weeds controlled through soybean canopy closure.

***Soybean Emergence and Yield***

In 2020, final stand counts differed by whole plot ($F_{3,12} = 7.71$, $p < .001$), with reduced stands occurring in NT compared to the living mulch treatments ($t_{12} = 0.58$, $p < .01$; Figure 2-3). In contrast, greater soybean yields were detected in NT compared to the living mulch treatments ($t_{44} = 0.39$, $p < .05$; Figure 2-4). However, yields in CT were similar to the cover crop treatments. There was a significant subplot treatment effect ($F_{2,45} = 15.94$, $p < .001$) in which yields were greater in WF and V3 compared Wd subplots (Figure 5). In 2021, final stand counts differed by whole plot ($F_{3,12} = 9.49$, $p < .01$). Similar to 2020, soybean stands were lower in NT compared to

CT and living mulch treatments (Figure 2-3). Overall, soybean yield was low across all treatments in 2021, however, greater yields were detected in CT compared to all cover crop treatments ($t_{44}$ = .9936, $p$ < .05; Figure 2-4). Similar to 2020, a subplot treatment effect ($F_{2,45}$ = 9.18, $p$ < .001) indicated that yields were greater in WF compared to Wd subplots (Figure 2-5).

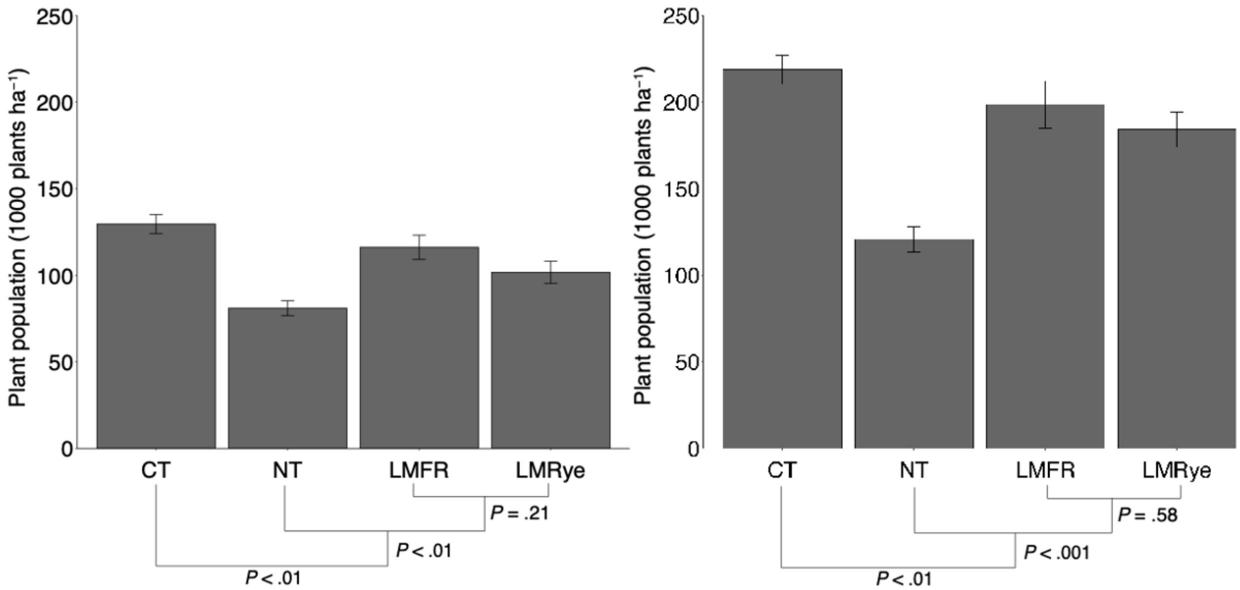


**Figure 2-3.** Final soybean stand counts ±SEM scaled to plants per hectare in 2020 in Upper Marlboro, MD (left) and 2021 in Beltsville, MD (right) in conventional-till (CT), no-till (NT), living mulch + forage radish residue (LMFR), and living mulch + rye residue (LMRye). *P*-values represent significance levels for contrasts of groups intersecting at those nodes.

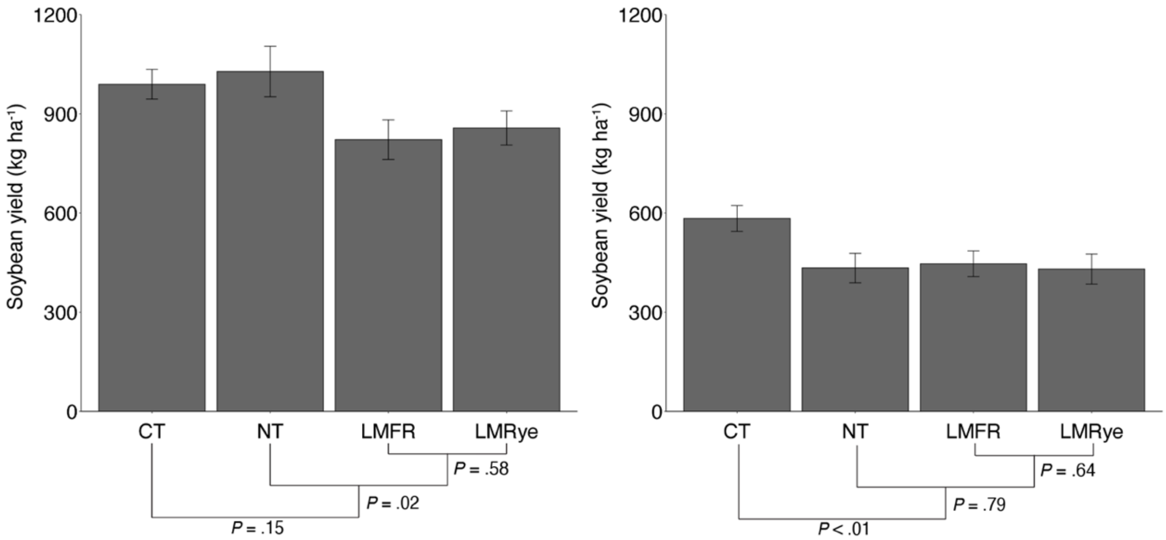


**Figure 2-4.** Soybean yield ±SEM within whole-plot treatments for 2020 in Upper Marlboro, MD (left) and 2021 in Beltsville, MD (right) field seasons; conventional-till (CT), no-till (NT), living mulch + forage radish residue (LMFR), and living mulch + rye residue (LMRye). *P*-values represent significance levels for contrasts of groups intersecting at those nodes.

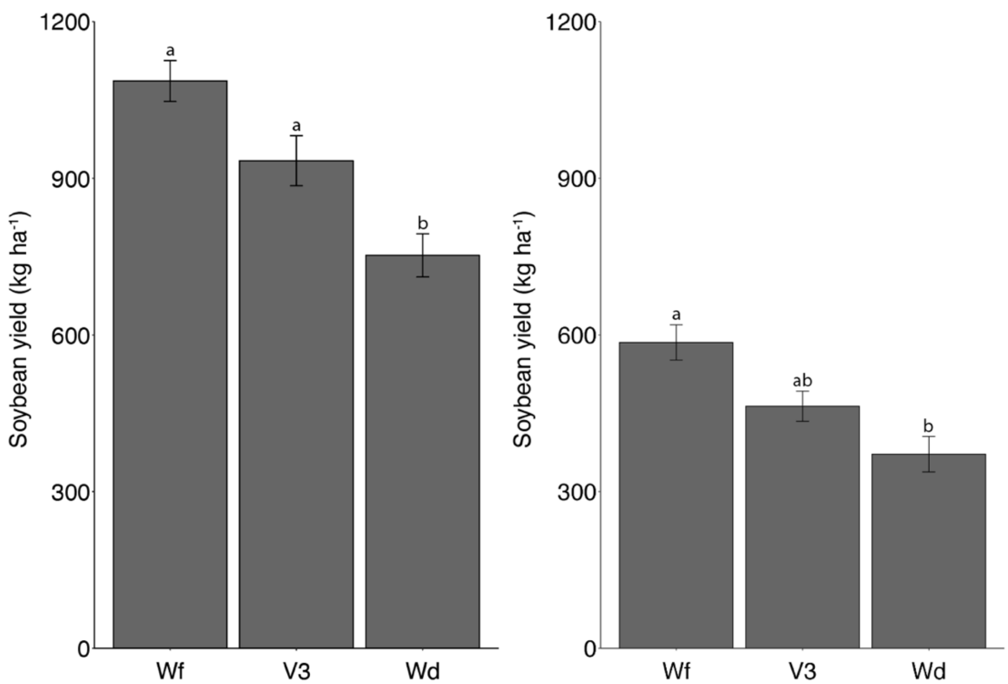


**Figure 2-5.** Soybean yield ±SEM within subplot treatments for 2020 (left) and 2021 (right) field seasons; weeds controlled through soybean canopy closure (Wf), weeds controlled through V3 soybean stage (V3), weedy all season (Wd). Bars show means and standard errors. Means bearing the same letter are not significantly different at the 5% probability level according to Tukey's honestly significant difference test ($P \leq .05$).

In 2020, greater yield and lower stand counts were detected in NT treatments. This suggests that reduced stands likely resulted from large amounts of residue interfering with seed placement by the planter. However, this reduced stand did not result in yield reductions. In another experiment investigating the impact of conventional tillage and cover crop residue on weed emergence and yield in soybean, Weber et al. (2017) found reduced weed density in NT compared to CT, however, soybean yield was lower in NT than the CT system due to poorer soybean stands. However, Weber et al. (2017) credited poorer stand establishment to the seeding equipment not being adequate for planting in high cover crop residue. Lower yield in living mulch treatments during the current experiment suggests competition between soybean plants and red clover may have occurred. Yield reductions in soybean-living mulch systems have been documented previously (Uchino et al., 2009). In 2021, the red clover was not completely terminated by the strip-tiller in the intra-row areas. Still, there was no evidence of competition between the soybean and red clover, possibly as a result of the patchy clover stands. Overall similar yield between WF and V3 subplots in both years suggests that cover crops alone may provide sufficient weed control following management through the CPWC.

## Practical Implications

The current experiment highlights the potential for annual cover crops and perennial clovers to be used over multiple growing seasons as part of a conservation tillage system. Self-seeding annual cover crops and continued establishment of perennial cover crops may be beneficial for growers experiencing challenges such as time of planting following fall harvest. Natural reestablishment may also be beneficial for growers that desire to avoid the added seed and labor expenses associated with replanting and/or prefer that their cover crops are established earlier in the growing season.

During this experiment, variation in weed species among treatments complicated findings. Still, taken together, these results highlight the potential of cover crop residues and/or perennial clovers to contribute to an IWM program for the suppression of weed species during the soybean CPWC. The no-till and living mulch operation deployed during this experiment may be especially useful for organic soybean producers who lack good herbicide options and want to reduce in-season tillage or conventional producers interested in reducing their herbicide applications. Reductions in weeds resulting from cover crop residues or living mulches may result in fewer spray applications, thereby placing less selection pressure on weeds, and subsequently reducing the likelihood for resistance development (Wallace et al., 2019). However, different cover crops can influence weed species differently (Didon et al., 2014). This suggests that future research evaluating different cover crop species and weed communities under disparate field and environmental conditions is needed to better understand the influences of self-seeded cover crop residues and perennial living mulches on weed germination, establishment, and maturation during the CPWC. Farmers can then be better informed regarding the benefits and risks of using cover crops to manage weeds under varying conditions.

# Chapter 3: Effect of Cover Crop Residues and Interplanted Red Clover on Predator Abundance, Pest Injury and Profit in Sweet Corn


## Abstract

Incorporating living mulches and cover crop residues within vegetable fields can enhance vegetation diversity and subsequently reduce crop injury by creating conditions less conducive to pest outbreaks. Field studies were conducted over three field seasons to investigate foliar predator abundance and subsequent crop damage caused by insect herbivores in sweet corn interplanted with a living mulch and/or cover crop residues. Whole plot treatment included one of the following cover cropping approaches: (1) conventionally-tilled (bare-ground), (2) no-till with cover crop residue, (3) living mulch + spring terminated cover crop residue, and (4) living mulch + winter killed residue. Subplot treatment included one of the following herbicide practices: (1) an at-planting application of residual herbicides (herbicide) or (2) no herbicide application (no herbicide). Predator abundance on sweet corn plants increased throughout the growing season, however, species abundance, richness and diversity remained similar among treatments. Further, similar amounts of pest injury to sweet corn ears were detected between treatments at crop harvest. Results from one field season indicated that similar profits can be obtained between conventionally-tilled sweet corn inclusive of synthetic herbicides and cover crop diversified treatments with and without herbicide application. As such, the incorporation of cover crop residues and living mulches into sweet corn production may not result in increased predator abundance or enhanced biological control of herbivorous pests but may result in similar profits in small scale sweet corn plantings in the Mid-Atlantic region.


## Introduction

The adoption of monoculture cropping systems has led to a reduction in predatory insects and shifted the balance in favor of insect herbivores (Bianchi et al., 2006). Incorporating living mulches and cover crop residues into vegetable fields can enhance habitat complexity within cropping systems. This, in turn, can increase the abundance of natural enemies and subsequently decrease herbivorous pest abundance (Root, 1973). The corn earworm (CEW), *Helicoverpa zea* is a significant pest of multiple field and vegetable crops throughout the western hemisphere (Capinera, 2020; Harding, 1976; Martin et al., 1976), and is one of the most devastating and difficult to manage insect pests in the United States (Kennedy & Storer, 2000). Sweet corn (*Zea mays*) is a preferred host plant for CEW oviposition (Fitt, 1989; M. W. Johnson et al., 1975). Consequently, the CEW is one of the most important pests affecting sweet corn production (V. M. Moore & Tracy, 2021). Following oviposition and hatching of CEW eggs on silks and ear husks, neonate larvae move down the silk tube into the husk of developing ears within a few hours. There, they remain protected from external risks including predators, parasitoids and insecticide sprays.

Additional sweet corn pests include stink bugs (Hemiptera: Pentatomidae), sap beetles (typically *Carpophilus lugubris*) and the European corn borer (*Ostrinia nubilalis*). In the Mid-Atlantic region, European corn borer populations and associated crop damage have been significantly reduced over the past decade as a result of widespread adoption of genetically modified corn varieties expressing insecticidal proteins (Dively et al., 2018). However, genetically modified crops have had a lesser impact on other sweet corn pests. As such, additional pest suppressive tools such as biological control are needed. Minute pirate bugs (*Orius* spp.) and lady beetles (Coccinellidae) are omnivorous predators that feed on insect eggs and soft-bodied insects, as well as plant resources such as pollen (Eubanks & Denno, 1999; Lattin, 1999; Ugine et al., 2022). These and other generalist predators can contribute significantly to insect pest suppression in cropping systems (Symondson et al., 2002), and previous research has attributed significant field mortality of CEW eggs to minute pirate bugs and lady beetles (Manandhar & Wright, 2016; Seagraves & Yeargan, 2009).

Greater in-field habitat complexity can enhance populations of insect natural enemies by providing them additional food and shelter (D. Landis et al., 2000). Studies have demonstrated greater numbers of generalist predators and in some instances, a reduction in pests and associated crop damage, in diversified vegetable plantings (Cai et al., 2010; D. Landis et al., 2000; Rivers et al., 2020). Kahl et al. (2019) found greater numbers of big-eyed bugs (*Geocoris* spp.), minute pirate bugs and lady beetles, as well as lower numbers of insect pests in cucumber interplanted with a red clover (*Trifolium pratense*) living mulch. A living mulch is a cover crop interplanted with a cash crop that remains alive throughout the cash crop growing season. Similarly, Manandhar and Wright (2016) found an increased number of minute pirate bugs in sweet corn interplanted with buckwheat (*Fagopyrum esculentum*) compared to monoculture sweet corn. Hinds and Hooks (2013) found lower numbers of insect herbivores and more generalist predators in zucchini (*Cucurbita pepo*) interplanted with a sunn hemp (*Crotalaria juncea*) living mulch compared to monoculture zucchini.

In addition to augmenting insect natural enemies, cover crop residues and living mulches can contribute to weed suppression in vegetable systems (Mennan et al., 2020). A living mulch (red clover) and cover crop residue (rye, *Secale cereale* or forage radish, *Raphanus sativus*) combination suppressed weeds as well as conventional herbicide sprays in sweet corn (V. L. Johnson et al., 2023). In the current study, we investigated the potential of these same cover crop treatment combinations to enhance generalist predator numbers on the sweet corn foliage and reduce sweet corn insect pest abundance and associated injury to sweet corn ears. The economic feasibility of incorporating cover crop residues and interplanted red clover living mulch into sweet corn production was also investigated. We hypothesized that there would be an increased number of foliar predators potentially resulting in a reduction in pest injury to sweet corn ears in cover crop diversified compared to monoculture treatment plots.

## Materials and Methods

### *Experimental Design and Field Operations*

Field experiments were conducted in 2019, 2020, and 2021 at the Central Maryland Research and Education Center in Upper Marlboro, MD (lat: 38.859079°, long: -76.778731°, year 1), and roughly 16 km away in Beltsville, MD (lat: 39.011440°, long: -76.833356°, years 2 and 3). Soils at the study sites are Annapolis series (fine-loamy, glauconitic, mesic Typic Hapludults) (Upper Marlboro) and a Russett-Christiana complex where the Russett surface soil is classified as loam or sandy loam and the Christiana surface soil is classified as silt loam (Beltsville). This study was part of a larger research project investigating cover cropping impacts on weeds, beneficial arthropods and insect pests. Treatments were arranged in a Latin square: split-plot design with four replicates. Whole plot treatments included: (1) conventional till (CT), (2) no-till with cover crop residue (NT), (3) living mulch + cover crop residue (LMRye), and (4) living mulch + winter killed residue (LMFR). The split-plot factor consisted of herbicide treatments: (1) an at-planting application of residual herbicides (herbicide) or (2) no herbicide application (no herbicide). Herbicides used included a pre-emergence combination of 1.68 kg ai $ha^{-1}$ atrazine and 1.42 kg ai $ha^{-1}$ S-metolachlor. Herbicides were broadcasted in NT and CT herbicide subplots and banded within the strips (intra-row area) of the forage radish (LMFR) or rye (LMRye) in living mulch herbicide subplots. Main plots measured 82.8 $m^2$ (9.1 m × 9.1 m) and each subplot measured 41.9 $m^2$ (4.6 m × 9.1 m).

During early fall, a mixture of crimson clover (*Trifolium incarnatum;* 3.36 kg $ha^{-1}$), forage radish (*Raphanus sativus*; 3.9 kg $ha^{-1}$), and cereal rye (*Secale cereale* L. 'Aroostook'; 62.8 kg $ha^{-1}$) was planted in CT and NT plots. In living mulch treatments, rows alternated between two rows of red clover (*Trifolium pratense*) and three rows of cereal rye (75.1 kg $ha^{-1}$) or forage radish (11.2 kg $ha^{-1}$) in LMRye and LMFR plots, respectively. Red clover was seeded at a rate of 9 kg $ha^{-1}$ in LMRye and 16.8 kg $ha^{-1}$ in LMFR plots. All cover crops were drilled at an interrow spacing of 15.2 cm. In the spring, when the rye reached anthesis, cover crops in CT plots were mowed, plowed, and incorporated into the soil. Crimson clover senesced naturally, and the forage radish was winter killed in 2019 and 2020. A roller crimper was used to terminate the rye in the NT and LMRye treatments, and temporarily slow red clover growth in LMRye and LMFR plots. In late May, sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) [variety: Providence (Syngenta, Wilmington, DE)] was seeded into each plot at an inter-row spacing of 76.2 cm, resulting in 12 crop rows per plot. In LMRye and LMFR plots, sweet corn seeds were planted within the center of the strips of forage radish or rye residue. Plots were overhead irrigated to mitigate periods of low rainfall and a split-application of 28-0-0-5S with boron fertilizer was applied at a rate of 44.8 kg $ha^{-1}$ at planting, and side dressed at a rate of 112.1 kg $ha^{-1}$. Weeds were manually removed weekly throughout the duration of the experiment. As part of the larger investigation involving weeds, half of each whole plot received an at-planting application of residual herbicides. It was presumed that the herbicide applications would not impact the arthropod community. However, arthropod sampling was conducted separately within each subplot treatment. Timing of field tasks is provided in Table 3-1.

**Table 3-1.** Timing of field operations in 2019 (Upper Marlboro, MD), 2020, and 2021 (Beltsville, MD).

| Field Operation | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| Planted cover crops | 14 Sept 2018 | 5 Sept 2019 | 16 Sept 2020 |
| Terminated cover crops | 23 May 2019 | 25 May 2020 | 28 May 2021 |
| Planted + fertilized sweet corn | 23 May 2019 | 25 May 2020 | 1 June 2021 |
| Fertilizer side dressed | 2 July 2019 | 24 June 2020 | 1 July 2021 |

### *Foliar Arthropod Counts*

Visual counts of arthropods inhabiting corn plants were performed weekly beginning roughly 30 days after sweet corn planting (DAP) and continued through the silking stage (R1). During each sampling event, ten randomly chosen corn plants per plot were thoroughly searched, and all arthropods encountered were identified to the lowest taxonomic level possible, counted and recorded by developmental stage.

### *Harvest Damage Assessment and Crop Yield*

To determine the level of insect damaged sweet corn ears, all ears within the center 7.6 m of eight interior rows within each plot were harvested, counted, and rated for insect damage. During rating events, all harvested ears were opened, and the presence of CEW damage as well as the number of kernels damaged by sap beetles and stink bugs were recorded. Damage was determined to be caused by sap beetles when hollowed kernels and/or sap beetle larvae were observed (Dowd 2000). Kernels were considered damaged by stink bugs when sunken and or discolored as a result of stylet puncture wounds (Cissel et al. 2015). Ears were considered damaged by corn earworm when fully consumed silks and kernels were observed. No sampling for damage caused by the European corn borer was performed because damage levels were expected to be imperceptible as a result of areawide pest suppression in the Mid-Atlantic region

(Dively et al., 2018). Yield was measured from the interior rows as described in Johnson et al. (2023b).

***Economic Assessment***

Sweet corn cost and profit analysis were performed using budget computations created by University of Maryland Extension (2023). The following formula was used to calculate net profit (P):

$$P = I - (C_v + C_f)$$

where I = income generated from sweet corn yields, $C_v$ = variable costs, and $C_f$ = fixed costs (Supp. Mat. 1). Variable costs ($C_v$) consisted of seeds, fertility, chemicals, irrigation expenses (electric, fuel, repair/maintenance), harvest labor, and interest on operating capital. Fixed costs ($C_f$) consisted of planting, field preparation, crop maintenance, interest on spring custom rates, irrigation payments, and land charges. Income from sweet corn produced in each treatment plot was calculated by counting the number of dozens of harvested ears and multiplying this number by the market price reported by the Virginia Department of Agriculture and Consumer Services (2021). Variable costs were determined using local costs from seed and chemical dealers and averaged, and the 2023 University of Maryland Extension custom rate survey was used to determine fixed costs in the absence of individual farm expenses (Dill & Bruce, 2023). Using custom rates provides a proxy of fixed costs related to production practices for the enterprise budget, as machinery ownership and operating costs are difficult to calculate and make up a large portion of expenses for farmers (Pflueger, 2005).

***Statistical Analysis***

Permutational multivariate ANOVAS (PERMANOVA) were used to test for significant differences in community composition across treatments (M. J. Anderson, 2017). If a significant effect was detected, Indicator Species Analyses were performed to identify which species were more commonly associated with which treatment. Total abundance of all predatory arthropod species was summed within each treatment replicate and analyzed using linear mixed models (LMM) to test for differences in total predator abundance with treatment (CT, NT, LMFR, and LMRye), sample date, and their interaction as fixed effects. Only species making up > 1% of the total insect abundance were considered for analysis.

LMMs were also used to test for differences in the percent of harvested sweet corn ears containing CEW damage and the number of kernels per ear containing sap beetle and stink bug damage. LMMs were also used to test for differences in net profit. When the LMM indicated a significant difference between treatment means, post-hoc pairwise comparisons were performed using Tukey-adjusted *p*-values (Lenth, 2020). All data were log transformed when necessary to stabilize the variances. All statistical analyses were performed using R (v. 4.1.2; R Core Team 2021). linear mixed effects models were built using the package 'lme4'(Bates et al., 2015). Post-hoc means comparisons were performed using the package 'emmeans' (Lenth, 2020). PERMANOVA community analyses were performed using the 'vegan' package, and Indicator Species Analyses were performed using the package 'indicspecies' (De Cáceres & Legendre, 2009). All figures were made using the 'ggplot2' package (Wickham, 2009).

## **Results**

### ***Foliar Arthropods***

A total of 10,306 arthropods representing 22 different taxa were observed from all locations over the three year-study. A total of 3,855 herbivores (37% of all arthropods) representing 14 families and 6,451 predators (63% of all arthropods) representing nine families were collected. The most abundant herbivorous taxa were leafhoppers (Cicadellidae; 43%), flea beetles (Chrysomelidae; 27%) and tarnished plant bugs (Miridae; 8%). The most abundant predatory taxa were minute pirate bugs (69%), lady beetles (21%), and spiders (Araneae; 8%). There was no subplot treatment effect on arthropod abundances. As such, foliar arthropod analysis was conducted at the whole plot level.

In 2019, PERMANOVA results revealed that no species sampled were more commonly associated with any treatment (Pseudo-F = 0.68, $p$ = 0.1). Mean predator abundance differed by treatment ($\chi^2$ = 19.45, df = 3, $p$ < 0.001) and sample date ($\chi^2$ = 89.12, df = 3, $p$ < 0.001). No treatment by date interaction was detected ($\chi^2$ = 15.13, df = 9, $p$ = 0.09). Predator abundance was lower in both living mulch treatments compared to NT and CT (Fig. 3-1). Predator abundance was greatest at the final sampling event compared to all previous dates.

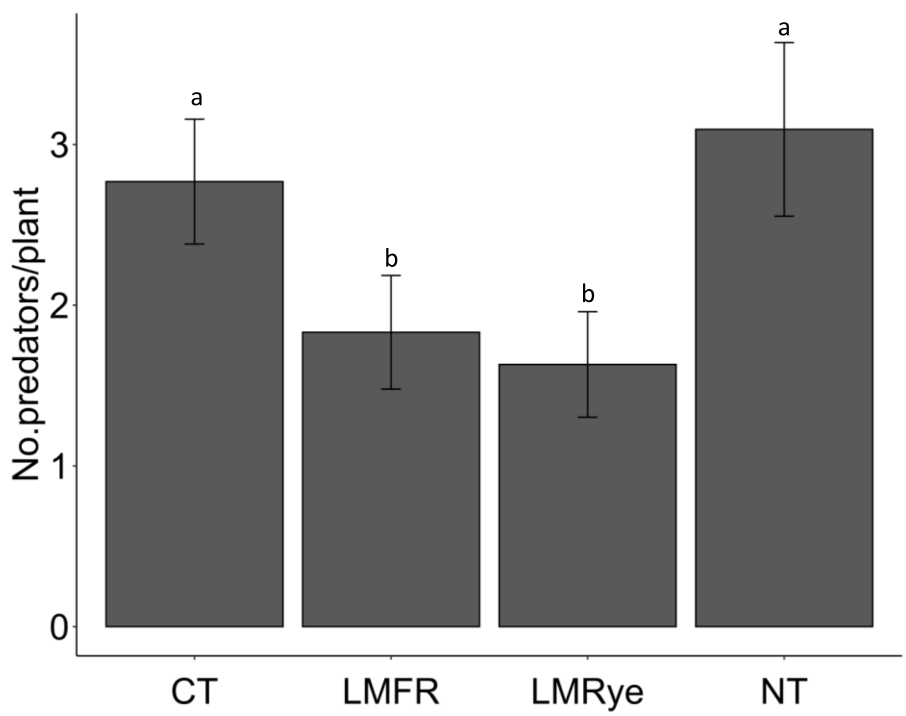


**Figure 3-1.** Mean number of predators ±SEM per sweet corn plant found in four cover cropping treatments averaged over four sampling periods in 2019. The CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter a are not significantly different at the 5% probability level.

Analogous to 2019, no species were more commonly associated with a treatment (Pseudo-F = 1.36, $p$ = 0.21) in 2020. Total predator abundance differed by sample date ($\chi^2$ = 186.45, df = 3, $p$ < 0.001), with significantly more predators occurring later in the growing season. However, no treatment effect ($\chi^2$ = 5.34, df = 3, $p$ = 0.15) or treatment by date interaction was detected ($\chi^2$ = 7.69, df = 9, $p$ = 0.57; Fig. 3-2).

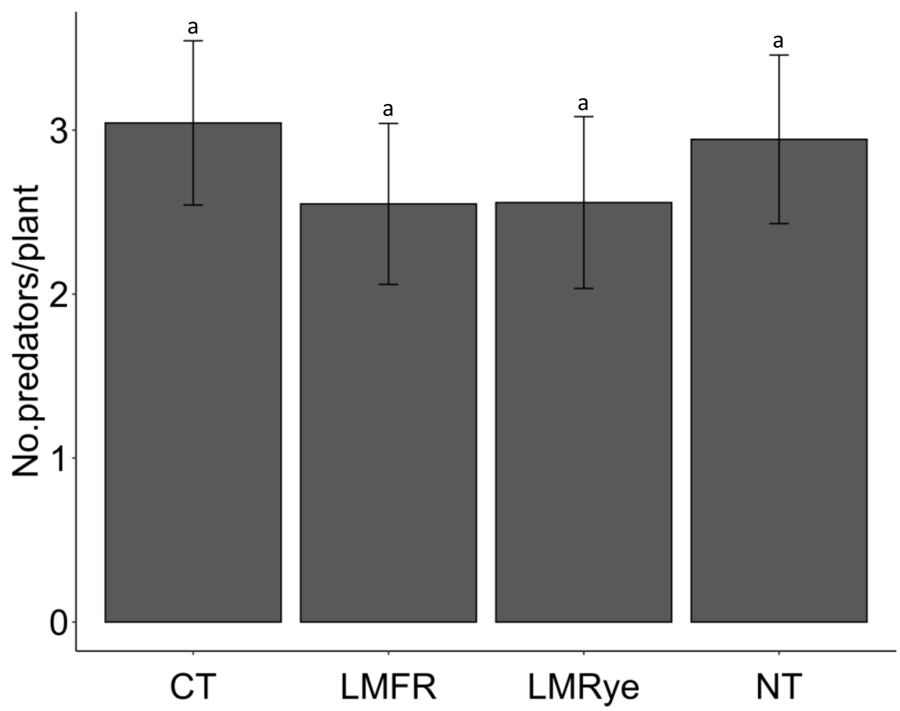


**Figure 3-2.** Mean number of predators ±SEM per sweet corn plant found in four cover cropping treatments averaged over four sampling periods in 2020. The NT indicates no-till, CT is conventional till, LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter a are not significantly different at the 5% probability level.

As in previous years, in 2021 no species were more commonly associated with any treatment (Pesudo-F = 0.35, $p$ = 0.80). However, total predator abundance differed by treatment ($\chi^2$ = 8.81, df = 3, $p$ < 0.05), sample date ($\chi^2$ = 582.06, df = 3, $p$ < 0.001), and their interaction ($\chi^2$

= 28.13, df = 3, $p < 0.001$). More predators were detected in CT and NT treatments compared to LMRye and in CT compared to LMFR at 54 DAP (Fig. 3-3). More predators were also detected in all treatments with each subsequent sample date.

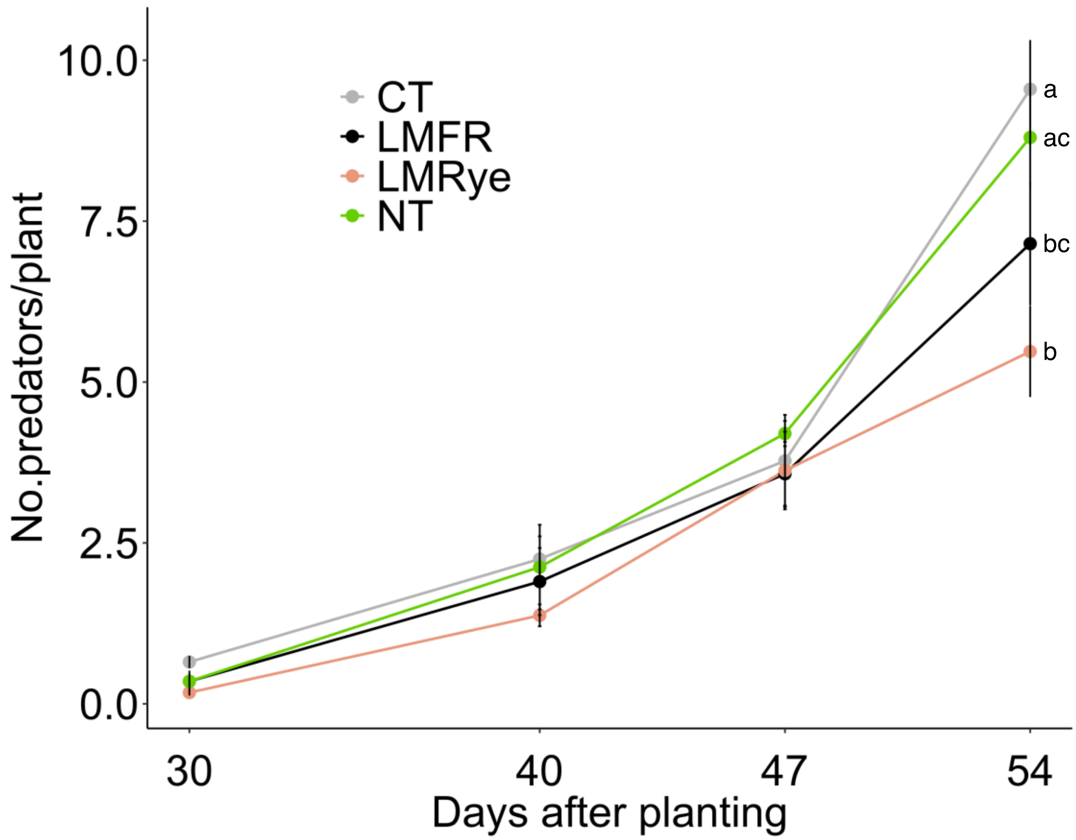


**Figure 3-3.** Mean number of predators per sweet corn plant in four cover cropping treatments during four sampling periods in 2021. The CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter a are not significantly different at the 5% probability level. Missing letters between treatments within sample dates indicates all means are not significantly different at the 5% probability level.

### *Corn Damage, Yield and Profit*

The planting equipment used in 2019 resulted in poor seed placement and establishment. Thus, the corn had to be replanted resulting in differing maturity periods among corn plants within plots. Therefore, yield and harvest damage could not be measured in 2019. In 2020 and 2021, a total of 3,788 sweet corn ears were checked for insect damage. Of this total, 2,097 ears (55%) were found to be damaged by CEW and 2,100 kernels (8%) displayed sap beetle feeding injury. Stink bugs were responsible for the least amount of ear injury. A total of 162 kernels (0.8%) displayed stink bug feeding injury. Similar to foliar arthropods, there was no subplot treatment effect. As such, injury data were analyzed at the whole plot level.

In 2020, a treatment effect was detected on the average number of kernels per ear exhibiting sap beetle damage ($F_{3,11} = 3.78$, $p = 0.04$). However, *p*-value corrections resulting from Tukey pairwise comparisons did not detect any treatment differences (Table 3-2). The percent of total harvested sweet corn ears exhibiting corn earworm damage was similar between treatments ($F_{3,11} = 2.08$, $p = 0.16$). Further, the number of kernels exhibiting stink bug damage was also equivalent between treatments ($F_{3,11} = 0.04$, $p = 0.99$). In 2021, no treatment effect was detected in the percentage of CEW damaged ears ($F_{3,11} = 0.96$, $p = 0.44$) or the number of kernels exhibiting sap beetle damage ($F_{3,12} = 3.11$, $p = 0.07$; Table 3-1). The amount of stink bug damage ears averaged 0.04 injured kernels per ear in NT and no stink bug injured kernels were found in the other treatments. As such, stink bug damage in 2021 was too low for analysis. Overall, yield was similar between all treatments in 2020. In 2021, subplot differences within treatments occurred, with all untreated subplots yielding lower than their herbicide treated equivalents (Fig. 3-4; Johnson et al. 2023b).

**Table 3-2**. Mean ± SEM sweet corn ear damage in 2020 and 2021.

| Treatment[1] | CEW % Damaged ears | Sap beetle #kernels $ear^{-1}$ | Stink bug #kernels $ear^{-1}$ |
|---|---|---|---|
| | | 2020 | |
| CT | 38.37 ± 5.26 | 5.90 ± 2.06 | 0.13 ± 0.05 |
| LMFR | 44.22 ± 3.70 | 1.82 ± 0.60 | 0.53 ± 0.43 |
| LMRye | 44.89 ± 5.32 | 1.43 ± 0.39 | 0.49 ± 0.49 |
| NT | 53.94 ± 4.16 | 3.40 ± 0.79 | 0.11 ± 0.07 |
| | | 2021 | |
| CT | 62.39 ± 3.00 | 0.14 ± 0.02 | 0.00 ± 0.00 |
| LMFR | 67.04 ± 7.06 | 0.08 ± 0.05 | 0.04 ± 0.00 |
| LMRye | 72.22 ± 3.40 | 0.21 ± 0.10 | 0.00 ± 0.00 |
| NT | 64.37 ± 2.33 | 0.00 ± 0.00 | 0.00 ± 0.00 |

[1]CT = conventional till, LMFR = living mulch + forage radish residue, LMRye = living mulch + rye residue and NT = no-till.

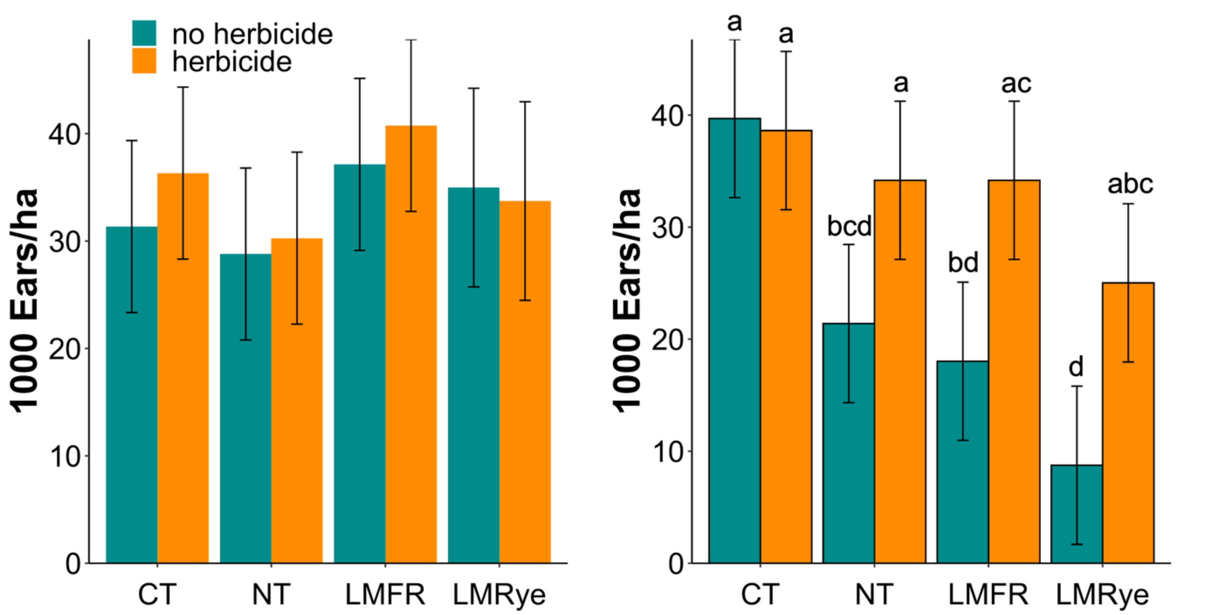


**Figure 3-4.** Sweet corn yield ± SEM in 2020 (left) and 2021 (right). The CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Orange bars indicate herbicide treated subplots and blue bars indicate untreated subplots. Means bearing the same letter a are not significantly different at the 5% probability level.

There were no significant effects of treatment ($\chi^2$ = 3.97, df=3, $p$ = 0.27), subplot ($\chi^2$ = 1.83, df=1, $p$ = 0.18), or their interaction ($\chi^2$ = 1.69, df=3, $p$ = 0.64) on net profit in 2020 (Fig. 3-5). Due to significant differences in yield among treatments and subplots in 2021, significant effects of treatment ($\chi^2$ = 23.32, df=3, $p$ < 0.001), subplot ($\chi^2$ = 44.43, df=1, $p$ < 0.001), and their interaction ($\chi^2$ = 19.27, df=3, $p$ < 0.001) on net profit were detected in 2021 (Fig. 3-5). Overall, herbicide treated production systems were more profitable than their untreated equivalents except in CT, which had similar profits between herbicide and untreated subplots. Further, all herbicide treated cover crop systems (NT, LMFR, and LMRye) were as profitable as CT, while untreated NT, LMFR, and LMRye experienced reduced profits compared to CT. Total production costs for all treatment-subplot combinations reported in Table 3-4.

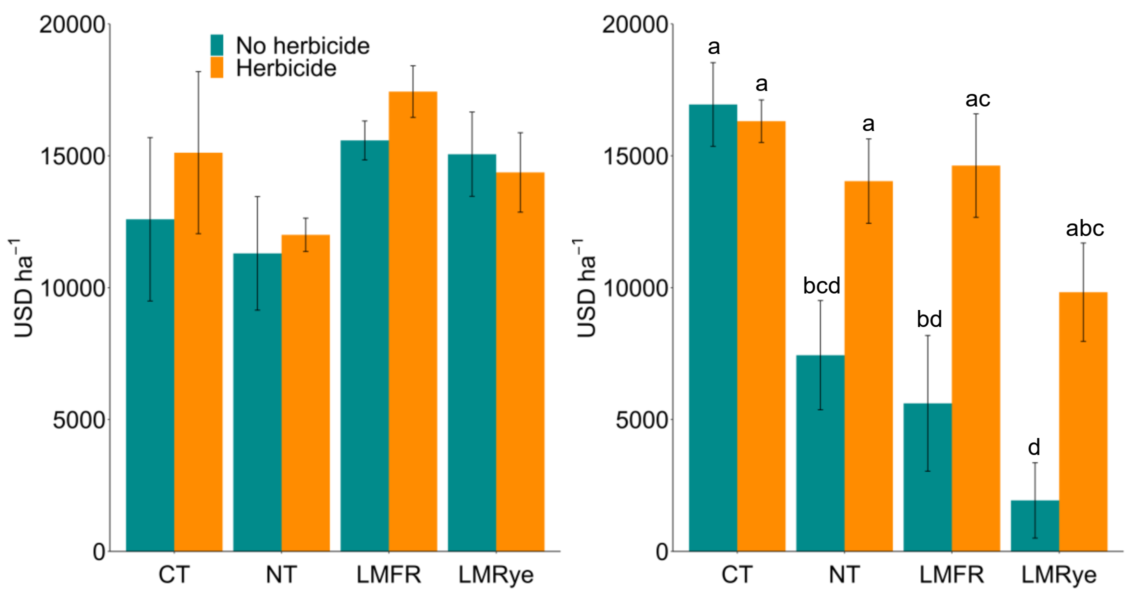


**Figure 3-5.** Net profit ± SEM in 2020 (left) and 2021 (right). The CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Orange bars indicate herbicide treated subplots and blue bars indicate untreated subplots. Means bearing the same letter a are not significantly different at the 5% probability level.

**Table 3-3.** Total production cost for each treatment.

| Treatment[-1] | Herbicide | No Herbicide |
|---|---|---|
| | -----------USD ha$^{-1}$ ----------- | |
| CT | 3,833 | 3,762 |
| NT | 3,791 | 3,721 |
| LMFR | 3,762 | 3,726 |
| LMRye | 3,790 | 3,753 |

[1]CT = conventional till, LMFR = living mulch + forage radish residue, LMRye = living mulch + rye residue and NT = no-till.

## Discussion

A primary objective of this study included assessing the ability of a living mulch (red clover) and cover crop residue (rye or forage radish) combination and cover crop residue (NT) alone to increase the abundance of generalist predators on corn plants, and subsequently reduce insect injury to sweet corn ears. Our hypothesis was that there would be a greater number of generalist predators on corn foliage in the cover crop diversified (NT, LMFR and LMRye) as opposed to monoculture (CT) sweet corn plantings. We further hypothesized that increases in generalist predators might reduce pest damage in diversified plantings. However, during each study year, generalist predator numbers were mostly similar among treatments. In 2019, overall lower predator abundance was detected in both living mulch treatments compared to CT and NT treatments while no treatment differences were detected on any sample dates in 2020 and 2021. During each year, predator abundance on corn foliage increased as the season progressed in all treatments, potentially due to increases in pest abundance during sweet corn silking. Further, no differences in herbivore damage to harvested sweet corn ears were detected between treatments during each study year. As such, input costs and total yield were the only variable factors potentially contributing to treatment differences in net profit. Consequently, yields were analogous among all treatment plots in 2020 resulting in similar profits. In contrast, yield reductions in non-herbicide treated cover crop (NT, LMRye, LMFR) subplots in 2021 resulted in lower profits compared to CT non-herbicide treated subplot and all treatment subplots receiving herbicides. Johnson et al., 2023b conjectured that the reduction in yield observed in untreated cover crop subplots in 2021 was induced by early season water stress that caused competition between the cover crop and sweet corn for water and/or nitrogen.

Previous studies comparing predator abundance on corn foliage between diversified and monoculture field and sweet corn plantings have reported mixed results. Findings related to treatment effects on ear damage have also varied. Most of these studies investigated the effects of border, rather than interplanted vegetation on predator abundance and crop damage. In contrast to the current study, more foliar predators and lower stink bug and corn earworm damage was detected in field corn bordered by strips of partridge pea (*Chamaecrista fasciculata*) compared to corn plantings neighboring mowed natural vegetation (Hunt et al. 2021). In another study, greater predator diversity and density were found on sweet corn foliage surrounded by a more diverse semi-natural habitat compared to corn surrounded by annual crops (M. A. Altieri & Whitcomb, 1980). However, total ear damage caused by corn earworm remained similar among treatments (M. A. Altieri & Whitcomb, 1980). Similar to the current study, Johnson et al. (2023a), found no differences in the total number of predators found on sweet corn foliage bordered by strips of flowering marigold (*Tagetes patula*) compared to monoculture sweet corn plantings; and the number of insect damaged sweet corn ears was also analogous among treatments.

Predator movement between plots may have contributed to the lack of treatment differences observed in this experiment. Previous experiments have documented higher rates of insect movement across borders in plots less than 9m wide, as well as in isolated plots separated by areas of non-crop vegetation (Prasifka et al., 2005). The 9.1m wide plots in this experiment, combined with mowed corridors between plots may have impeded our ability to detect significant treatment differences. In addition to this, many generalist predators, including lady beetles and minute pirate bugs are highly mobile (Lahiru Ishan Samaranayake & Costamagna, 2019; Obrycki & Kring, 1998). As the most abundant predators observed in this experiment, it is likely that high rates of movement between treatments occurred.

In some instances, the nectar produced by the added vegetation may be exploited by insect pests and subsequently enhance the energetic state of herbivores within crop fields (Winkler et al., 2009). During this study, adult CEW moths were frequently observed feeding on nectar from red clover flowers in living mulch treatments. Nuttycombe (1930) noted increased oviposition by adult CEW that fed on red clover flowers. However, during the current study, the presence of the red clover did not increase the number of ears damaged by CEW in living mulch treatments. As such, the presence of the red clover appeared to be neutral with respect to enhancing foliar predator abundance and pest injury.

Previous research investigating consumer attitudes towards food production has identified a growing interest in more sustainable production practices and an increased demand for crops produced with fewer inputs (Rana & Paul, 2017). Studies have attributed numerous environmental benefits to cover crops, including alleviated drought stress, enhanced soil quality, increased nutrient cycling, and increased weed suppression (Hartwig & Ammon, 2002). Moreover, inter-seeding red clover has been expressly identified as an environmentally friendly production practice capable of improving the resilience of cropping systems to a multitude of biotic and abiotic stresses (Gaudin et al., 2013). Still, cover crop adoption remains low, with cover crops occurring on roughly 5% of the total cropped area in the U.S. (Deines et al., 2022).

Studies investigating the perceived barriers to cover crop adoption frequently list establishment costs and investment return as leading impediments (Duke et al., 2022; Dunn et al., 2016).

Analysis of the costs and net returns associated with treatments investigated in this study support, in part, the economic feasibility of incorporating cover crop residues and interplanted red clover living mulch into sweet corn production. Results from 2020 highlight the potential for similar profits to be obtained between conventionally tilled sweet corn inclusive of synthetic herbicides and cover crop diversified treatments with and without herbicides. Though insect pest control expenses were not factored into the current study, similar levels of harvest damage suggest they would be identical across all production practices investigated, and as such, would not alter the significance of profit margins between treatments.

Taken together, these findings suggest that while cover crop residues and living mulches may provide adequate weed suppression in sweet corn production (V. L. Johnson et al., 2023) and have the potential to maintain similar profit margins to conventional production, additional measures are still needed to manage insect pests. As such, more research is needed to fully understand the economic feasibility and advantages of incorporating cover crop residues and living mulches into sweet corn production.

# Chapter Four: Interplanted Red Clover Influences Populations of Beneficial Arthropods in Sweet Corn

**Abstract**

Agricultural intensification and conversion of natural landscapes to crop production fields have contributed to declines in insect biodiversity including species of natural enemies and pollinators. Increasing the number of plant species within a habitat may be a method used to enhance insect biodiversity and provide other eco-services. Perennial cover crops are increasingly being recognized for their ability to suppress weeds and improve soil health when incorporated into cropping systems. In this study, the influence of an interplanted red clover (*Trifolium pratense*) in combination with cover crop residues on arthropod natural enemy abundance and pollinator richness and visitation rates was evaluated and compared with monoculture sweet corn plots. Whole plot treatment included four cover cropping methods: (1) conventionally-tilled (bare-ground), (2) no-till with cover crop residue, (3) living mulch + spring terminated cover crop residue, and (4) living mulch + winter killed residue. Subplot treatment included herbicide practice: (1) an at-planting application of residual herbicides (herbicide) or (2) no herbicide application (no herbicide). Several families of parasitoids and predators representing multiple taxa were enhanced in sweet corn interplanted with red clover. Additionally, bumblebees and lepidopteran pollinators were frequently observed foraging red clover flowers. Overall, this study provides evidence that the inclusion of red clover living mulch in combination with terminated cover crop residues can increase the abundance of some insect natural enemies while simultaneously serving as a food source for pollinators in crop fields.

**Introduction**

Beneficial arthropods are influenced by many components of a habitat, including the availability of nectar, pollen and alternative prey, as well as habitable microclimates and other abiotic conditions that facilitate their survival (Sheehan, 1986). Reductions in plant diversity and richness and intensification of agricultural practices associated with large monoculture plantings have reduced the availability of these necessities in modern agroecosystems and subsequently caused major declines in insect biomass and biodiversity including pollinators and natural enemies of crop pests (Raven & Wagner, 2021). This has further contributed to declines in biological control and pollination services (Matson et al., 1997; Sánchez-Bayo & Wyckhuys, 2019). Increasing in-field plant diversity via the incorporation of cover crop residues and living mulches can help support beneficial arthropods by restoring many of these essential resources (Hartwig & Ammon, 2002).

A living mulch is a cover crop interplanted with a cash crop that remains alive throughout the cash crop growing season. Previous research investigating the effects of living mulches on beneficial arthropods has found more predators and parasitoids, and reduced herbivorous insects in living mulch diversified systems (Hinds & Hooks, 2013; Kahl et al., 2019; Manandhar & Wright, 2016). Habitat diversification resulting from the addition of living or dead cover crop mulch has also been associated with an increased abundance of epigeal predators. For example, spiders, predatory ground beetles and ants were found to be more abundant in cropping systems containing living mulches or cover crop residues (Altieri et al. 1985, Hooks and Johnson 2004, Landis et al. 1987).

A perennial cover crop that can be used as a living mulch to influence arthropod natural enemies and pollinators in red clover, *Trifolium pratense*. Red clover is a short-lived perennial often recognized for its ability to increase soil fertility (McKenna et al., 2018) and suppress weeds (Mutch et al., 2003; Johnson et al., 2023). Red clover remains established throughout the growing season, contains nectar and pollen, and produces a dense mat of vegetation that can serve as a refuge and source of alternative prey (Gaudin et al., 2013; Morrison, 1961). Previous research investigating the influence of red clover on natural enemy abundance found increased numbers of generalist predators in cucumber interplanted with red clover compared with monoculture cucumber plots (Kahl et al., 2019). Higher numbers of epigeal and/or foliar natural enemies were also found in tomato (*Solanum lycopersicum*), corn (*Zea mays*) and cauliflower (*Brassica oleracea* var. *Botrytis*) plots containing red clover compared to clean cultivated plots (Miguel A. Altieri et al., 1985a). Further, lab studies evaluating the suitability of different floral resources for parasitoids showed that red clover flowers increased the longevity and parasitism rates of *Trichogramma* spp., (Díaz et al., 2012). Despite these findings, limited research has been conducted to better understand the effects of interplanted red clover on natural enemy populations in vegetable systems.

Pollinator's success may also be influenced by the diversity of plants within a habitat (Gavini et al., 2021; Nicholls & Altieri, 2013). Pollinators provide a crucial ecosystem service required for the maintenance of natural (Aguilar et al., 2006) and domesticated (Klein et al., 2007) plant communities. Though honey bees are often considered the primary crop pollinators, over 400 species of wild, non-*Apis* bees have been documented in Maryland (MD DNR, 2015). Similar to other groups of beneficial arthropods, pollinator populations are declining (Cameron et al., 2011; Colla et al., 2012; Council, 2007; Potts et al., 2010; vanEngelsdorp et al., 2009). Although no single factor can fully explain their decline, habitat loss and fragmentation have been recognized as common drivers (Brown & Paxton, 2009; Goulson et al., 2008; Winfree et al., 2009). To this point, fragmented landscapes developed from the establishment of annual cropping systems often support lower pollinator diversity and abundance than natural landscapes (Potts et al., 2010; Winfree et al., 2009).

Intensively managed fields dominated by monoculture plantings create a less hospitable environment for pollinators. This is partially credited to flowers being generally available only while crops are in bloom. During periods preceding and following crop bloom, these habitats are unsuitable for foraging bees (Winfree, 2008). The addition of flowering cover crops within agricultural fields can provide pollinators a supplementary food source (Saunders et al., 2013). Red clover typically flowers from early spring through fall, providing an important source of nectar to wild bee species for an extended period (Baude et al., 2016; N. M. Williams et al., 2012). Red clover is also a preferred plant for foraging bumble bees (Carvell et al., 2006; Goulson et al., 2005; Kleijn & Raemakers, 2008) and has a positive impact on bumblebee reproduction (Rundlöf et al., 2014). Several studies have examined the effectiveness of pollinators for seed production in red clover (Rao & Stephen, 2009; Wermuth & Dupont, 2010). However, few studies have investigated the ability of red clover to serve as a food source for bees and other pollinators in vegetable systems. In addition, leaving residue on the soil surface as a result of conservation tillage can also benefit pollinators by providing nesting habitats (Cusser et al., 2023). As such, the purpose of the current study, was to investigate the effectiveness of a red clover living mulch and cover crop residue combination to enhance insect natural enemies and pollinators within sweet corn plantings. We hypothesized that there would be an increased number of insect predators, parasitoids and pollinators in cover crop diversified compared to monoculture sweet corn plantings.

## Materials & Methods

### *Experimental Design and Field Operations*

Field experiments were conducted in 2019, 2020 and 2021 at the Central Maryland Research and Education Center in Upper Marlboro, MD (lat: 38.859079°, long: -76.778731°, year 1), and roughly 16 km away in Beltsville, MD (lat: 39.011440°, long: -76.833356°, years 2 and 3). Soils at the study sites are Annapolis series (fine-loamy, glauconitic, mesic Typic Hapludults) (Upper Marlboro) and a Russett-Christiana complex where the Russett surface soil is classified as loam or sandy loam and the Christiana surface soil is classified as silt loam (Beltsville). This study was part of a larger research project investigating cover cropping impacts on weeds and crop development (V. L. Johnson et al., 2023), beneficial arthropods, and insect pests. Treatments were arranged in a Latin square: split-plot design with four replicates. Whole plot treatments included: (1) conventional till (CT), (2) no-till with cover crop residue (NT), (3) living mulch + cover crop residue (LMRye), and (4) living mulch + winter killed residue (LMFR). The split-plot factor consisted of herbicide treatments: (1) an at-planting application of residual herbicides (herbicide) or (2) no herbicide application (no herbicide).

During early fall, a mixture of crimson clover (*Trifolium incarnatum;* 3.36 kg $ha^{-1}$), forage radish (*Raphanus sativus*; 3.9 kg $ha^{-1}$), and cereal rye (*Secale cereale* L. 'Aroostook'*;* 62.8 kg $ha^{-1}$) was planted in CT and NT plots. In living mulch treatments, rows alternated between two rows of red clover (*Trifolium pratense*) and three rows of cereal rye (75.1 kg $ha^{-1}$) or forage radish (11.2 kg $ha^{-1}$) in LMRye and LMFR plots, respectively. Red clover was seeded at a rate of 9 kg $ha^{-1}$ in LMRye and 16.8 kg $ha^{-1}$ in LMFR plots. All cover crops were drilled at an interrow spacing of 15.2 cm. In the spring, when the rye reached anthesis, cover crops in CT plots were mowed, plowed and incorporated into the soil. Crimson clover senesced naturally, and the forage radish was winter killed. A roller crimper was used to terminate the rye in the NT and LMRye treatments, and temporarily slow red clover growth in LMRye and LMFR plots. In late May, sweet corn (*Zea mays* convar. *saccharata* var. *rugosa*) [variety: Providence (Syngenta, Wilmington, DE)] was seeded into each plot at an inter-row spacing of 76.2 cm, resulting in 12 crop rows per plot. In LMRye and LMFR plots, sweet corn seeds were planted within the center of the strips of forage radish or rye residue. Plots were overhead irrigated to mitigate periods of low rainfall and a split-application of 28-0-0-5S with boron fertilizer was applied at a rate of 44.8 kg $ha^{-1}$ at planting, and side dressed at a rate of 112.1 kg $ha^{-1}$. Weeds were manually removed weekly throughout the duration of the experiment. As part of the larger investigation involving weeds, half of each whole plot received an at-planting application of residual herbicides. It was presumed that the herbicide applications would have no impact on the insect community. However, insect sampling was conducted separately within each subplot treatment. Timing of field tasks is provided in Table 4-1.

**Table 4-1.** Timing of field operations in 2019 (Upper Marlboro, MD), 2020, and 2021 (Beltsville, MD).

| Field Operation | Year 1 | Year 2 | Year 3 |
|---|---|---|---|
| Planted cover crops | 14 Sept 2018 | 5 Sept 2019 | 16 Sept 2020 |
| Terminated cover crops | 23 May 2019 | 25 May 2020 | 28 May 2021 |
| Planted + fertilized sweet corn | 23 May 2019 | 25 May 2020 | 1 June 2021 |
| Fertilizer side dressed | 2 July 2019 | 24 June 2020 | 1 July 2021 |

***Arthropod Natural Enemies***

Yellow sticky cards were used to assess the aerial community of small arthropods within treatment plots. One card was secured to wooden dowels using clothespins within the center of each subplot. All cards (7.6 x 12.7 cm) were oriented perpendicular to sweet corn rows with both sides exposed. The first of two sampling events occurred when sweet corn in the control (CT) treatment reached the V6 stage (i.e., six defined leaves per plant were visible). The second sampling event took place when sweet corn in the CT treatment reached the R1, or emerging silk stage. At the V6 stage, cards were placed just above the height of the red clover at approximately 46 cm above the soil surface in all treatments. On the second sampling date, cards were placed such that the top of the card was even with the tip of the surrounding sweet corn ears. Cards remained exposed for 7 days, after which they were collected and placed in clear re-sealable plastic bags, frozen, and stored in the lab for later identification.

Pitfall traps were used to sample the epigeal arthropod community using the same design described by Dively (2005). Two pitfall traps were placed in the center area of each subplot with one trap located within the sweet corn row and the other located in the interrow area. Pitfall traps were set on two sample dates. The first sampling event was initiated during a late vegetative corn stage and the next at the R3 stage to coincide with the period of time when mature earworm larvae would likely be exiting the ear and entering the soil to pupate. After 7 days, cups containing captured arthropods preserved in propylene glycol were collected and stored for future identification. All organisms were later identified to the lowest taxonomic level possible. Soil emergence cage traps (MegaView Science Co., Ltd. Taiwan) were used to provide an additional means for sampling epigeal natural enemies during late crop cycle (sweet corn maturity). One emergence cage (60 x 60cm) was randomly placed between two sweet corn rows per subplot. Cages were established using propylene glycol as the collection agent immediately following sweet corn harvest. All arthropods collected after a seven-day period were stored in the lab and later identified to the lowest taxonomic level possible.

***Pollinator Richness and Visitation***

Bee bowl traps were used to sample pollinator richness within each treatment during the sweet corn growing season. Although sweep net sampling provides a more accurate representation of the overall pollinator community (Prado et al., 2017), this was not a feasible method due to the spatial arrangement of the clover and sweet corn plants. Instead, methods similar to Wheelock and O'Neal (2016) were used at each trapping station. In brief, 103.5ml

SOLO brand plastic cups were painted florescent yellow, blue or white and filled halfway with a soapy water solution. A single cup of each color was placed on a stand. Stands were constructed using wooden stakes, and bee bowls were positioned just above the height of the red clover, or approximately 46 cm above the soil surface in all treatments. The bowls were deployed for a 24-hour period, during the V3, V9, and corn tasseling stages. At sweet corn tasseling, tiered stands constructed from 1.83m wooden stakes were used. Each stand contained three sets of each colored bee bowls. The first set of bowls were placed at 2.5cm above the soil surface, the second at ear height, and the final at corn tassel height (Figure 4-1). One tiered stand was established per subplot.

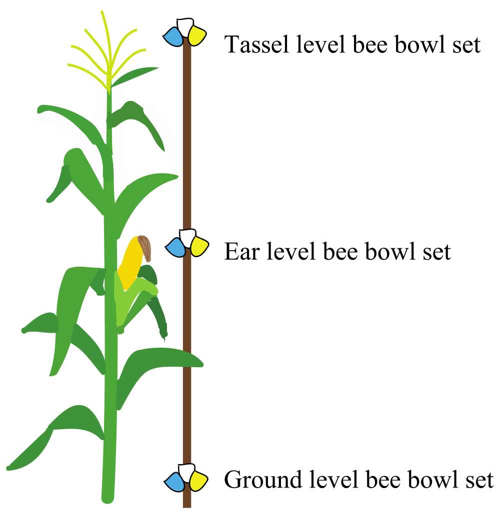


**Figure 4-1.** Placement of three-tiered bee bowl stand relative to sweet corn plant.

Visual observations of pollinators visiting red clover flowers were performed weekly throughout the sweet corn growing season. Observations of pollinators visiting clover flowers were performed for five minutes by a single individual moving slowly in a single direction through each LMFR and LMRye subplot. Two sets of observations were performed per sample date, with one set taking place between 8:30 and 10:00am and the second between 1:00 and 2:00 pm. Observations of pollinators visiting sweet corn tassels were similarly performed per subplot in all treatments during sweet corn pollen shed. All pollinators observed were classified according to the University of Maryland Native Pollinator Survey (Bernauer et al., 2016) and recorded. In brief, easily recognizable bees such as honeybees (*Apis mellifera*), bumble bees (*Bombus* spp.), large carpenter bees (*Xylocopa virginica*), and long-horned bees (*Eucera* spp.) were recorded, while more difficult to identify bees were grouped into morphospecies categories such as: large dark bee, metallic green bee, small dark bee, etc.

***Statistical Analysis***

Species richness (number of taxa) and diversity (Shannon-Weiner index) were computed per plot using the 'vegan' package (Oksanen et al., 2022), and linear models (LM) were used to test for treatment differences. The total abundance of all predators and parasitoids were summed within each treatment replicate and analyzed using generalized linear mixed models (GLMM) to test for differences in total abundance with treatment (CT, NT, LMFR, and LMRye), sample date, and their interaction as fixed effects. Only species making up > 1% of the total natural enemy abundance were considered for analysis. Generalized linear models (GLM) were used to test for differences in abundance of individual taxa. When analyses indicated a significant difference between treatment means, post-hoc pairwise comparisons were performed using Tukey-adjusted *p*-values (Lenth, 2020).

All comparisons were made at the whole-plot level, as subplot treatments did not influence any investigated measure of richness, diversity, or abundance. All data were log transformed when necessary to stabilize the variances. All statistical analyses were performed using R (v. 4.1.2; R Core Team 2021). All linear models were built using the package 'lme4'(Bates et al., 2015). Post-hoc means comparisons were performed using the package 'emmeans' (Lenth, 2020). All figures were made using the 'ggplot2' package (Wickham, 2009).

## **Results**

### ***Yellow Sticky Cards***

A total of 59,553 arthropods representing 93 different taxa were identified from sticky card samples over the three field experiments. The community of arthropods consisted of herbivores (32%), predators (28%), parasitoids (27%), and detritivores (9%). The remaining 4% were unspecified arthropods, fungivores and pollinators. The most abundant herbivores were leafhoppers (Cicadellidae; 52%), thrips (Thripidae; 31%), and leaf beetles (Chrysomelidae; 4%). The most abundant predators captured were minute pirate bugs (Anthocoridae; 78%), lady beetles (Coccinellidae; 14%), and long-legged flies (Dolichopodidae; 4%). The most abundant parasitoids were represented by wasps in the families Scelionidae (25%), Mymaridae (20%), and Trichogrammatidae (16%). Picture-winged flies (Ulidiidae; 73%) and flesh flies (Sarcophagidae; 26%) were the most abundant detritivores.

Significant differences in natural enemy (parasitoid and predator) richness ($F_{3,12} = 5.02$, $p = 0.02$) and diversity ($F_{3,12} = 35.00$, $p < 0.001$) were detected in samples collected during the V6 corn growth stage in 2019 in Upper Marlboro. At the R1 stage, significant treatment differences were again detected in species diversity ($F_{3,12} = 6.87$, $p = .01$); however, no differences in richness were detected ($F_{3,12} = 0.96$, $p = 0.44$). At both sample dates, greater species diversity occurred in both living mulch treatments (LMFR and LMRye) compared to CT and NT (Table 4-2). Species richness was greater in LMFR compared to CT, and LMRye compared to CT and NT at the vegetative sampling stage.

**Table 4-2.** Richness (± SEM) and diversity (± SEM) of all natural enemies captured on yellow sticky cards in four treatments at two corn growth stages in 2019.

| Treatment | Richness ± SEM | Diversity ± SEM |
|---|---|---|
| | --- V6 corn stage --- | |
| CT | 17.50 ± 0.96 b | 2.02 ± 0.06 b |
| LMFR | 21.25 ± 1.03 a | 2.44 ± 0.05 a |
| LMRye | 20.75 ± 0.48 ac | 2.42 ± 0.03 a |
| NT | 18.75 ± 0.48 bc | 1.98 ± 0.03 b |
| | --- R1 corn stage --- | |
| CT | 27.00 ± 1.22 a | 2.03 ± 0.09 b |
| LMFR | 31.25 ± 1.97 a | 2.33 ± 0.07 a |
| LMRye | 31.75 ± 1.31 a | 2.39 ± 0.04 a |
| NT | 30.00 ± 1.41 a | 2.06 ± 0.07 b |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level.

Total predator abundance differed by treatment ($\chi^2 = 14.52$, df = 3, $p < 0.01$), sample date ($\chi^2 = 9.14$, df = 1, $p = 0.01$) and there was an interaction effect ($\chi^2 = 31.59$, df = 3, $p < 0.001$). A greater abundance of predators was detected in CT and NT compared to LMRye, and in CT compared to LMFR at the R1 stage (Figure 4-2). Similarly, total parasitoid abundance differed by treatment ($\chi^2 = 19.11$, df = 3, $p < 0.001$), sample date ($\chi^2 = 18.36$, df = 1, $p < 0.001$), and there was a significant interaction ($\chi^2 = 46.44$, df = 3, $p < 0.001$; Figure 4-2). At V6, greater parasitoid abundance was detected in both living mulch treatments compared to NT, and in LMFR compared to CT. No treatment differences were detected at R1.

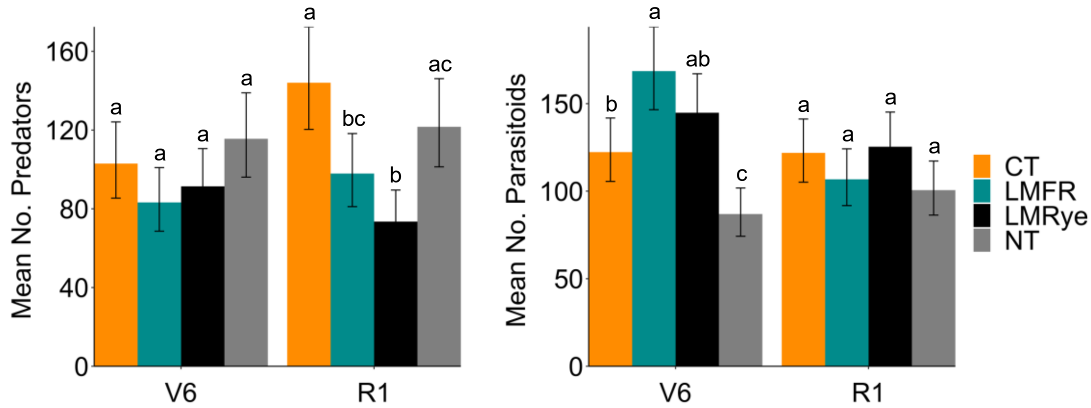


**Figure 4-2.** Mean number of total predators (left) and parasitoids (right) collected from yellow sticky cards at two sweet corn stages in 2019 (Upper Marlboro, MD). CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level within sample dates.

Four parasitoid families, Encyrtidae ($\chi^2 = 16.92$, df = 3, $p < 0.001$), Figitidae ($\chi^2 = 20.11$, df = 3, $p < 0.001$), Scelionidae ($\chi^2 = 22.21$, df = 3, $p < 0.001$), and Trichogrammatidae ($\chi^2 = 55.06$, df = 3, $p < 0.001$) and predatory family, Geocoridae($\chi^2 = 19.92$, df = 3, $p < 0.001$), were more abundant in both living mulch treatments compared to CT and NT (Table 4-3). In contrast, parasitoids in the family Ceraphronidae ($\chi^2 = 126.01$, df = 3, $p < 0.001$) and predators in the family Anthocoridae ($\chi^2 = 24.58$, df = 3, $p < 0.001$) were less abundant in living mulch treatments compared to CT and NT. No treatments differences were detected for Aphelinid ($\chi^2 = 4.53$, df = 3, $p = 0.21$), Eulophid ($\chi^2 = 0.19$, df = 3, $p = 0.98$), and Pteromalid ($\chi^2 = 7.47$, df = 3, $p = 0.06$) wasps or predators in the families Coccinellidae ($\chi^2 = 3.56$, df = 3, $p = 0.31$) and Dolichopodidae ($\chi^2 = 0.76$, df = 3, $p = 0.86$).

**Table 4-3.** Mean number (± SEM) of parasitoids and predators captured from sticky card sampling in 2019 (Upper Marlboro, MD).

| Guild | Family | CT | NT | LMFR | LMRye |
|---|---|---|---|---|---|
| Parasitoid | Aphelinidae | 1.3 ± 0.4 | 4.3 ± 1.8 | 3.9 ± 1.0 | 4.3 ± 1.0 |
| | Ceraphronidae | 43.8 ± 4.0 a | 18.0 ± 1.9 b | 12.9 ± 1.8 c | 6.9 ± 1.5 d |
| | Encyrtidae | 1.4 ± 0.5 b | 1.0 ± 0.2 b | 4.8 ± 1.5 a | 4.6 ± 0.7 a |
| | Eulophidae | 2.4 ± 0.5 | 2.8 ± 1.0 | 2.8 ± 0.8 | 2.8 ± 0.6. |
| | Figitidae | 10.6 ± 2.1 b | 14.0 ± 3.3 b | 29.8 ± 6.5 a | 32.0 ± 3.2 a |
| | Mymaridae | 17.8 ± 1.1 | 17.9 ± 3.9 | 15.9 ± 2.0 | 16.5 ± 1.9 |
| | Pteromalidae | 7.9 ± 1.4 | 4.8 ± 1.4 a | 10.1 ± 1.8 | 7.6 ± 0.8 |
| | Scelionidae | 19.9 ± 1.7 b | 19.9 ± 1.1 b | 27.1 ± 1.7 a | 27.6 ± 1.8 a |
| | Trichogrammatidae | 16.6 ± 2.3 b | 10.8 ± 1.0 b | 28.6 ± 3.4 a | 30.3 ± 1.1 a |
| Predator | Anthocoridae | 103.6 ± 10.4 a | 102.8 ± 10.4 a | 65.8 ± 5.0 b | 60.5 ± 4.8. b |
| | Coccinellidae | 11.0 ± 2.8 | 10.1 ± 2.6 | 7.5 ± 1.9 | 5.3 ± 2.6 |
| | Dolichopodidae | 7.9 ± 2.2 | 6.5 ± 1.9 | 6.5 ± 1.5 | 5.6 ± 1.2 |
| | Geocoridae | 2.3 ± 1.0 b | 1.5 ± 0.6 b | 11.1 ± 2.1 a | 12.6 ± 3.9 a |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Missing letters across treatments indicate no significant treatment effects were found. Table consists of families of predators and parasitoids that represent 1% or greater of the total number of natural enemies captured.

In 2020, significant differences in natural enemy richness ($F_{3,11} = 4.97$, $p = 0.02$) were detected in sticky card samples taken during V6 (Table 4-4). Greater species richness was detected in LMRye compared to all other treatments. No differences were detected in diversity ($F_{3,11} = 0.47$, $p = 0.71$) at V6, or in richness ($F_{3,11} = 1.15$, $p = 0.37$) or diversity ($F_{3,11} = 1.50$, $p = 0.27$) at R1. Total predator abundance again differed by treatment ($\chi^2 = 46.25$, df = 3, $p < 0.001$), sample date ($\chi^2 = 102.63$, df = 1, $p < 0.001$) and there was a significant interaction ($\chi^2 = 21.01$, df = 3, $p < 0.001$; Figure 4-3). Greater predator abundance was detected at V6 in LMRye compared to all other treatments, and in LMFR compared to NT. Total parasitoid abundance differed by sample date ($\chi^2 = 21.63$, df = 1, $p < 0.001$) and there was a date by treatment interaction ($\chi^2 = 18.39$, df = 3, $p < 0.001$). However, no treatment effect was detected ($\chi^2 = 2.72$, df = 3, $p = 0.44$).

**Table 4-4.** Richness (± SEM) and diversity (± SEM) of all natural enemies captured on yellow sticky cards in four treatments at two corn growth stages in 2020 (Beltsville, MD).

| Treatment | Richness ± SEM<br># of species | Diversity ± SEM<br>Shannon Index |
|---|---|---|
| | --- V6 corn stage --- | |
| CT | 17.00 ± 0.71 b | 2.10 ± 0.06 |
| LMFR | 17.75 ± 1.25 ab | 2.07 ± 0.07 |
| LMRye | 21.67 ± 0.88 a | 2.15 ± 0.06 |
| NT | 16.50 ± 0.65 ab | 2.08 ± 0.02 |
| | --- R1 corn stage --- | |
| CT | 15.75 ± 1.65 | 2.16 ± 0.07 |
| LMFR | 18.75 ± 1.93 | 2.23 ± 0.01 |
| LMRye | 17.67 ± 0.33 | 2.31 ± 0.04 |
| NT | 19.00 ± 1.08 | 2.15 ± 0.08 |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue Means bearing the same letter are not significantly different at the 5% probability level. Missing letters indicate no significant treatment effects were found.

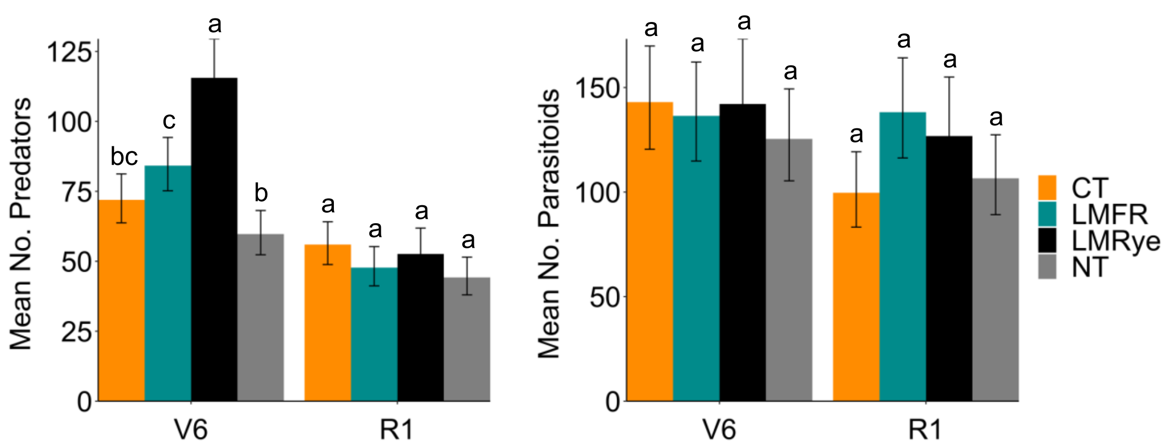


**Figure 4-3.** Mean number of total predators (left) and parasitoids (right) collected from yellow sticky cards at two sweet corn stages in 2020 (Beltsville, MD). CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level within sample dates. Graph consists of families of predators and parasitoids that represent 1% or greater of the total number of natural enemies captured.

Overall, greater parasitoid abundance occurred during the early sample period (V6).

Three parasitoid families, Platygastridae ($\chi^2 = 11.38$, df = 3, $p = 0.01$), Scelionidae ($\chi^2 = 11.56$, df

= 3, $p$ = 0.01), and Trichogrammatidae ($\chi^2$ = 42.13, df = 3, $p$ < 0.001), and one predatory family, Geocoridae ($\chi^2$ = 46.83, df = 3, $p$ < 0.001) were more abundant in both living mulch treatments compared to CT and NT in 2020 (Table 4-5). One parasitoid family, Ceraphronidae was more abundant in CT ($\chi^2$ = 30.08, df = 3, $p$ < 0.001), and no treatment differences were detected for three parasitoid families, Aphelinidae ($\chi^2$ = 1.44, df = 3, $p$ = 0.70), Figitidae ($\chi^2$ = 4.44, df = 3, $p$ = 0.22), and Mymaridae ($\chi^2$ = 1.08, df = 3, $p$ = 0.78), and two predator families, Coccinellidae ($\chi^2$ = 5.59, df = 3, $p$ = 0.13) and Anthocoridae ($\chi^2$ = 5.18, df = 3, $p$ = 0.16).

**Table 4-5.** Mean number (± SEM) of parasitoids and predators captured from sticky card sampling in 2020 (Beltsville, MD).

| Guild | Family | CT | NT | LMFR | LMRye |
|---|---|---|---|---|---|
| Parasitoid | Aphelinidae | 18.0 ± 5.8 | 20.4 ± 6.8 | 14.3 ± 3.7 | 11.8 ± 3.2 |
| | Ceraphronidae | 32.1 ± 6.1 a | 7.9 ± 1.5 b | 11.5 ± 2.4 b | 9.3 ± 1.5 b |
| | Figitidae | 2.9 ± 0.9 | 3.1 ± 1.0 | 5.1 ± 1.6 | 6.3 ± 1.8 |
| | Mymaridae | 35.1 ± 2.6 | 37.0 ± 1.7 | 41.0 ± 6.9 | 38.7 ± 3.6 |
| | Platygastridae | 1.3 ± 0.6 b | 3.5 ± 0.9 ab | 2.3 ± 0.8 ab | 5.5 ± 1.4 a |
| | Scelionidae | 22.6 ± 1.5 b | 35.1 ± 4.1 ab | 40.9 ± 5.4 a | 36.3 ± 4.4 ab |
| | Trichogrammatidae | 11.0 ± 1.5 b | 10.0 ± 2.0 b | 25.1 ± 2.6 a | 26.7 ± 3.4 a |
| Predator | Anthocoridae | 43.9 ± 7.6 | 30.4 ± 7.2 | 48.1 ± 10.1 | 64.8 ± 17.3 |
| | Coccinellidae | 19.6 ± 3.3 | 20.9 ± 4.0 | 13.0 ± 4.6 | 9.8 ± 1.4 |
| | Geocoridae | 0.5 ± 0.3 b | 0.8 ± 0.3 b | 4.9 ± 1.2 a | 9.5 ± 1.9 a |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Missing letters indicate no significant treatment effects were found. Table consists of families of predators and parasitoids that represent 1% or greater of the total number of natural enemies captured.

In 2021, significant differences in natural enemy richness were detected from sticky card samples taken during the R1 corn growth stage ($F_{3,12}$ = 4.74, $p$ = 0.02; Table 4-6). At R1, greater species richness occurred in LMFR compared to CT. No differences were detected in natural enemy richness ($F_{3,12}$ = 2.23, $p$ = 0.14) or diversity at V6 ($F_{3,12}$ = 1.23, $p$ = 0.34), or in diversity at R1 ($F_{3,12}$ = 0.94, $p$ = 0.45). Total predator abundance differed by sample date ($\chi^2$ = 682.42, df = 1, $p$ < 0.001) and there was a significant sample date by treatment interaction ($\chi^2$ = 14.19, df = 3,

$p < 0.01$). However, no treatment effect was detected ($\chi^2 = 7.17$, df = 3, $p = 0.07$). Overall greater predator abundance was detected at R1 compared to V6 (Figure 4-4). A significant effect of treatment ($\chi^2 = 7.79$, df = 3, $p = 0.05$), sample date ($\chi^2 = 15.17$, df = 1, $p < 0.001$) and their interaction ($\chi^2 = 20.85$, df = 3, $p < 0.001$) on total parasitoid abundance was detected. At V6, greater parasitoid abundance was detected in LMRye compared to CT (Figure 4-4).

**Table 4-6.** Richness (± SEM) and diversity (± SEM) of all natural enemies captured on yellow sticky cards in four treatments at two corn growth stages in 2021 (Beltsville, MD).

| Treatment | Richness ± SEM | Diversity ± SEM |
|---|---|---|
| | --- V6 corn stage --- | |
| CT | 18.75 ± 1.19 | 2.37 ± 0.06 |
| LMFR | 18.00 ± 0.91 | 2.23 ± 0.09 |
| LMRye | 21.75 ± 1.31 | 2.27 ± 0.06 |
| NT | 19.50 ± 0.96 | 2.38 ± 0.04 |
| | --- R1 corn stage --- | |
| CT | 17.25 ± 0.75 b | 2.03 ± 0.12 |
| LMFR | 20.25 ± 0.63 a | 2.21 ± 0.12 |
| LMRye | 19.75 ± 0.48 ab | 2.20 ± 0.03 |
| NT | 17.50 ± 0.87 ab | 2.07 ± 0.05 |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Missing letters indicate no significant treatment effects were found.

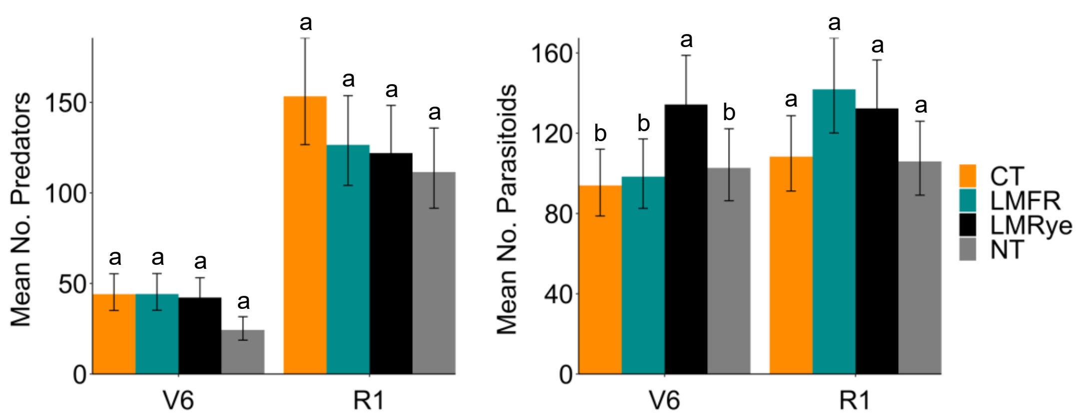


**Figure 4-4.** Mean number of total predators (left) and parasitoids (right) collected from yellow sticky cards at two sweet corn stages in 2021 (Beltsville, MD). CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the

5% probability level within sample dates. Graph consists of families of predators and parasitoids that represent 1% or greater of the total number of natural enemies captured.

Overall, greater parasitoid abundance was also detected at R1. The parasitoid family, Trichogrammatidae ($\chi^2 = 33.59$, df = 3, $p < 0.001$) and predatory family, Geocoridae ($\chi^2 = 30.63$, df = 3, $p < 0.001$) were more abundant in the living mulch treatments compared to CT and NT in 2021 (Table 4-7). One parasitoid family, Ceraphronidae ($\chi^2 = 10.84$, df = 3, $p = 0.01$) was less abundant in the living mulch treatments. No differences were detected for six parasitoid families: Aphelinidae ($\chi^2 = 6.22$, df = 3, $p = 0.10$), Encyrtidae ($\chi^2 = 4.33$, df = 3, $p = 0.23$), Eulophidae ($\chi^2 = 4.13$, df = 3, $p = 0.25$), Figitidae ($\chi^2 = 0.07$, df = 3, $p = 0.99$), Mymaridae ($\chi^2 = 6.11$, df = 3, $p = 0.11$), Scelionidae ($\chi^2 = 5.92$, df = 3, $p = 0.12$), and four predatory families: Anthocoridae ($\chi^2 = 0.50$, df = 3, $p = 0.92$), Coccinellidae ($\chi^2 = 2.55$, df = 3, $p = 0.47$), Dolichopodidae ($\chi^2 = 3.40$, df = 3, $p = 0.33$), and Formicidae ($\chi^2 = 2.18$, df = 3, $p = 0.54$).

**Table 4-7.** Mean number (± SEM) of parasitoids and predators captured from sticky card sampling in 2021 (Beltsville, MD).

| Guild | Family | CT | NT | LMFR | LMRye |
|---|---|---|---|---|---|
| Parasitoid | Aphelinidae | 18.0 ± 7.1 | 8.1 ± 2.4 | 7.3 ± 1.8 | 6.9 ± 1.0 |
| | Ceraphronidae | 15.0 ± 2.9 a | 9.3 ± 1.1 a | 7.1 ± 1.6 b | 7.8 ± 1.3 b |
| | Encyrtidae | 2.5 ± 0.7 | 4.8 ± 1.3 | 4.5 ± 1.2 | 6.8 ± 2.2 |
| | Eulophidae | 4.3 ± 1.4 | 2.1 ± 0.8 | 3.0 ± 0.8 | 1.9 ± 0.4 |
| | Figitidae | 11.0 ± 3.4 | 12.0 ± 3.4 | 10.9 ± 3.1 | 11.3 ± 2.9 |
| | Mymaridae | 14.9 ± 3.0 | 18.5 ± 2.4 | 24.0 ± 2.4 | 18.1 ± 2.7 |
| | Scelionidae | 23.8 ± 3.8 | 29.6 ± 2.3 | 26.0 ± 4.9 | 34.9 ± 2.0 |
| | Trichogrammatidae | 13.8 ± 1,8 b | 20.5 ± 2.9 b | 38.8 ± 4.8 a | 46.1 ± 6.9 a |
| Predator | Anthocoridae | 66.3 ± 17.8 a | 50.0 ± 16.2 b | 59.3 ± 17.7 a | 57.0 ± 13.4 a |
| | Coccinellidae | 18.3 ± 5.2 | 14.1 ± 4.4 | 15.8 ± 3.7 | 9.1 ± 3.0 |
| | Dolichopodidae | 7.3 ± 2.4 | 4.4 ± 1.3 | 3.6 ± 0.7 | 5.8 ± 0.9 |
| | Formicidae | 5.9 ± 4.6 | 0.8 ± 0.3 | 1.9 ± 1.7 | 3.8 ± 1.8 |
| | Geocoridae | 2.0 ± 0.9 b | 0.5 ± 0.3 b | 6.9 ± 1.3 a | 7.0 ± 1.4 a |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Missing letters indicate no significant treatment effects were found. Table consists of families of predators and parasitoids that represent 1% or greater of the total number of natural enemies captured.

***Emergence Cages***

A total of 27,170 arthropods representing 128 different taxa were identified from emergence cage samples during the two field experiments (2020, 2021). Samples consisted of herbivores (41%), detritivores (23%), parasitoids (18%), and predators (17%). The remaining 1% of arthropods collected were unspecified arthropods and pollinators. The most abundant herbivorous taxa were gall midges (Cecidomyiidae; 78%), leafhoppers (Cicadellidae; 5%), and wasps (Eurytomidae; 3%). The most abundant detritivores were frit flies (Chloropidae; 32%), midges (Ceratopgonidae; 17%), and minute black scavenger flies (Scatopsidae; 11%). The most abundant parasitoids were wasps in the families Mymaridae (34%), Scelionidae (29%) and Figitidae (9%). The most abundant predators were rove beetles (Staphylinidae; 49%), ants (Formicidae; 24%), and long-legged flies (Dolichopodidae; 7%). In 2021, no treatment differences in diversity were detected ($F_{3,12} = 1.33$, $p = 0.31$). However, a treatment effect on natural enemy richness was detected ($F_{3,12} = 7.64$, $p < 0.01$; Table 4-8). Species richness was lowest in CT.

**Table 4-8.** Richness (± SEM) and diversity (± SEM) of all natural enemies captured in emergence cages in 2020 and 2021 (Beltsville, MD).

| Treatment | Richness ± SEM | Diversity ± SEM |
|---|---|---|
| | --- 2020 --- | |
| CT | 18.00 ± 2.48 a | 2.21 ± 0.08 a |
| LMFR | 27.50 ± 2.99 a | 2.40 ± 0.07 a |
| LMRye | 24.67 ± 2.60 a | 2.09 ± 0.24 a |
| NT | 22.50 ± 0.87 a | 2.13 ± 0.20 a |
| | --- 2021 --- | |
| CT | 15.50 ± 2.33 b | 2.05 ± 0.09 a |
| LMFR | 24.50 ± 0.65 a | 2.32 ± 0.10 a |
| LMRye | 26.75 ± 2.10 a | 2.13 ± 0.23 a |
| NT | 26.25 ± 2.06 a | 2.38 ± 0.05 a |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level.

In 2020, no significant treatment differences in natural enemy richness ($F_{3,11} = 3.03$, $p = 0.08$) or diversity ($F_{3,11} = 0.82$, $p = 0.51$) were detected (Table 4-8). Total predator abundance differed by treatment ($\chi^2 = 91.90$, df = 3, $p < 0.001$, Figure 4-5), with the greatest number of predators detected in LMRye compared to all other treatments. Total predator abundance was also greater in NT compared to LMFR and CT and in LMFR compared to CT. Total parasitoid abundance differed by treatment ($\chi^2 = 249.35$, df = 3, $p < 0.001$, Figure 4-5), with the greatest number of parasitoids captured in both red clover treatments compared to CT and NT.

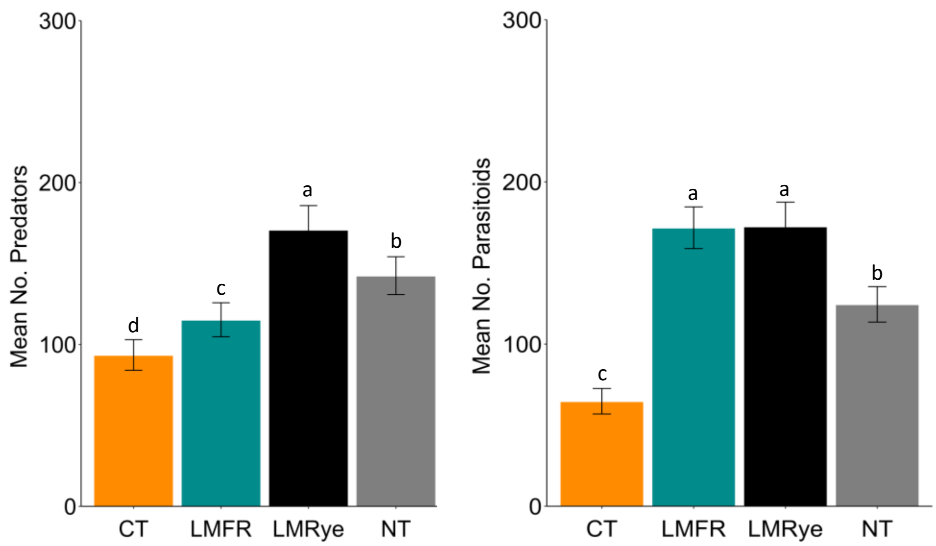


**Figure 4-5.** Mean number of predators (left) and parasitoids (right) collected from emergence cages in Beltsville, MD in 2020. CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Graph consists of families that represent 1% or greater of the total number of natural enemies captured.

Total parasitoid abundance was also greater in NT compared to CT. One parasitoid family: Braconidae ($\chi^2 = 10.35$, df = 3, $p = 0.02$) and one predatory family: Linyphiidae ($\chi^2 = 9.36$, df =

3, $p$ = 0.02) were more abundant in LMFR compared to CT (Table 4-9). Ceraphronidae ($\chi^2$ = 13.64, df = 3, $p < 0.01$) were more abundant in LMFR compared to CT and NT. Figitidae ($\chi^2$ = 17.43, df = 3, $p < 0.01$) were more abundant in NT compared to CT. Mymaridae ($\chi^2$ = 13.64, df = 3, $p < 0.01$) were more abundant in LMFR and LMRye compared to CT and NT, and in NT compared to CT. Platygastridae ($\chi^2$ = 15.87, df = 3, $p < 0.01$) were more abundant in LMRye compared to CT and NT. Finally, parasitoids in the family Trichogrammatidae ($\chi^2$ = 34.09, df = 3, $p < 0.001$) were more abundant in LMFR and LMRye compared to CT and NT. The predatory family Carabidae ($\chi^2$ = 10.87, df = 3, $p$ = 0.01) was more abundant in NT compared to CT. Dolichopodidae ($\chi^2$ = 14.98, df = 3, $p < 0.01$) were more abundant in CT compared to LMFR and LMRye, and Formicidae were more abundant in CT and LMRye compared to LMFR. Predatory beetles in the family Staphylinidae ($\chi^2$ = 224.63 df = 3, $p < 0.001$) were more abundant in LMRye compared to all other treatments, and in NT and LMFR compared to CT. No treatment differences were detected for one predatory family: Coccinellidae ($\chi^2$ = 5.65, df = 3, $p$ = 0.13).

**Table 4-9.** Mean number (± SEM) of parasitoids captured in emergence traps in 2020 (Beltsville, MD).

| Guild | Family | CT | NT | LMFR | LMRye |
|---|---|---|---|---|---|
| Parasitoid | Braconidae | 2.0 ± 1.1 b | 5.5 ± 2.6 ab | 6.3 ± 1.1 a | 5.0 ± 1.5 ab |
| | Ceraphronidae | 8.5 ± 1.2 b | 7.8 ± 2.1 b | 15.3 ± 0.9 a | 13.0 ± 0.6 ab |
| | Figitidae | 2.3 ± 1.1 b | 4.3 ± 0.9 ab | 5.8 ± 1.9 ab | 9.3 ± 2.6 a |
| | Mymaridae | 15.0 ± 1.6 c | 25.8 ± 3.42 b | 66.8 ± 17.1 a | 57.0 ± 4.2 a |
| | Platygastridae | 10.5 ± 1.7 b | 9.5 ± 4.6 b | 13.0 ± 5.5 ab | 20.0 ± 5.2 a |
| | Scelionidae | 19.0 ± 7.0 c | 61.8 ± 16.3 a | 43.3 ± 11.3 b | 45.0 ± 4.5 b |
| | Trichogrammatidae | 0.8 ± 0.5 b | 1.5 ± 0.9 b | 7.3 ± 2.2 a | 5.7 ± 0.9 a |
| Predator | Carabidae | 1.3 ± 0.9 b | 5.0 ± 2.1 a | 3.3 ± 1.4 ab | 2.0 ± 0.6 ab |
| | Coccinellidae | 4.0 ± 3.0 | 6.8 ± 2.7 | 3.3 ± 2.1 | 4.3 ±1.3 |
| | Dolichopodidae | 20.5 ± 5.5 a | 14.0 ± 3.9 ab | 13.0 ± 2.8 b | 9.7 ± 1.3 b |
| | Formicidae | 42.3 ± 15.8 a | 35.5 ± 14.3 ab | 27.0 ± 15.3 b | 41.3 ± 16.5 a |
| | Linyphiidae | 1.8 ± 0.3 b | 4.5 ± 1.3 ab | 5.8 ± 1.9 a | 4.0 ± 0.6 ab |
| | Staphylinidae | 23.3 ± 7.8 c | 76.3 ± 46.6 b | 62.5 ± 21.8 b | 109.0 ± 28.9 a |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Missing letters indicate no significant treatment effects were found. Table consists of families of parasitoids that represent 1% or greater of the total number of natural enemies captured.

In 2021, no treatment differences in natural enemy diversity were detected ($F_{3,12} = 1.33$, $p = 0.31$). However, a treatment effect richness was detected ($F_{3,12} = 7.64$, $p < 0.01$; Table 4-8). Species richness was lowest in CT. A significant effect of treatment on total predator abundance was detected ($\chi^2 = 400.93.35$, df = 3, $p < 0.001$, Figure 4-6), with greater predator abundance occurring in LMRye compared to all other treatments, and in LMFR and NT compared to CT. A significant effect of treatment on total parasitoid abundance was detected ($\chi^2 = 357.26$, df = 3, $p < 0.001$, Figure 4-6), with the greatest number of parasitoids captured in LMRye and NT compared to CT and LMFR. Parasitoid abundance was also greater in LMFR compared to CT.

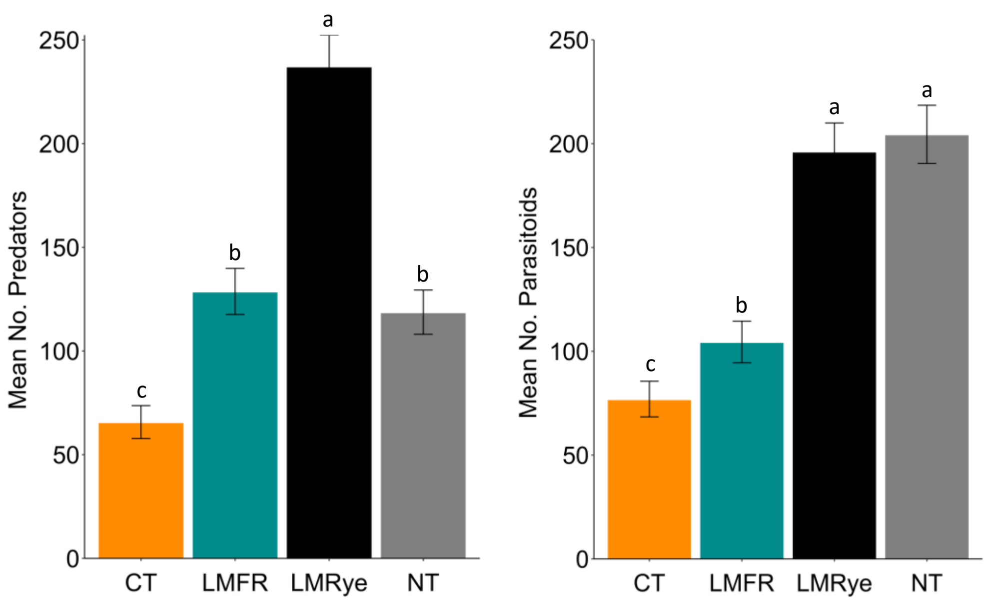


**Figure 4-6.** Mean number of predators (left) and parasitoids (right) collected from emergence cages in Beltsville, MD in 2021. CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Graph consists of families that represent 1% or greater of the total number of natural enemies captured.

Treatment differences for several natural enemy families were detected (Table 4-10). One parasitoid family, Braconidae ($\chi^2 = 15.22$, df = 3, $p = 0.02$) and one predatory family, Carabidae ($\chi^2 = 16.55$, df = 3, $p < 0.01$) were more abundant in LMRye compared to LMFR and CT. Parasitoids in the family Diapriidae ($\chi^2 = 23.40$, df = 3, $p < 0.001$) were more abundant in NT compared to all other treatments. Parasitoids in the family Encyrtidae ($\chi^2 = 35.08$, df = 3, $p < 0.001$) were more abundant in LMRye compared to CT and NT, and in LMFR compared to CT. The family Figitidae ($\chi^2 = 247.98$, df = 3, $p < 0.001$) was most abundant LMFR and decreased significantly in NT, LMFR, and CT; with the lowest abundance occurring in CT. Higher numbers of one parasitoid family, Mymaridae ($\chi^2 = 41.46$, df = 3, $p < 0.001$) occurred in LMRye compared to CT and NT, in LMFR compared to NT, and in NT compared to CT. Wasps in the family Trichogrammatidae ($\chi^2 = 12.21$, df = 3, $p < 0.01$) were more abundant in LMFR compared to all other treatments. One predatory family, Cantharidae ($\chi^2 = 61.84$, df = 3, $p < 0.001$) was more abundant in both red clover treatments compared to CT and NT. Dolichopodidae ($\chi^2 = 8.65$, df = 3, $p = 0.03$) was more abundant in LMFR compared to CT. Predators in the family Formicidae ($\chi^2 = 12.28$, df = 3, $p = 0.01$) were more abundant in NT compared to LMFR. Finally, predatory beetles in the family Staphylinidae ($\chi^2 = 578.85$, df = 3, $p < 0.001$) were most abundant in LMRye, with significantly fewer occurring in LMFR, NT, and CT. No treatment differences were detected for Linyphiidae ($\chi^2 = 3.12$, df = 3, $p = 0.37$).

**Table 4-10.** Mean number (± SEM) of parasitoids captured in emergence traps in 2021 (Beltsville, MD).

| Guild | Family | CT | NT | LMFR | LMRye |
|---|---|---|---|---|---|
| Parasitoid | Braconidae | 2.0 ± 1.7 b | 5.3 ± 0.9 ab | 2.3 ± 0.9 b | 6.5 ± 1.8 a |
| | Ceraphronidae | 10.3 ± 4.5 c | 23.3 ± 9.1 a | 7.5 ± 2.4 c | 14.3 ± 4.5 bc |
| | Diapriidae | 1.3 ± 1.0 b | 7.0 ± 2.1 a | 1.8 ± 0.5 b | 4.3 ± 0.5 b |
| | Encyrtidae | 0.5 ± 0.5 c | 2.0 ± 1.2 bc | 4.3 ± 3.6 ab | 7.8 ± 2.6 a |
| | Figitidae | 1.5 ± 1.5 d | 25.5 ± 12.5 b | 13.3 ± 8.4 c | 49.0 ± 17.0 a |
| | Mymaridae | 32.5 ± 10.2 c | 62.3 ± 16.8 b | 41.0 ± 3.4 ac | 127.0 ± 62.1 a |
| | Scelionidae | 27.3 ± 9.2 b | 74.3 ± 15.0 a | 28.8 ± 5.5 b | 60.3 ± 8.4 a |
| | Trichogrammatidae | 1.3 ± 0.5 b | 4.5 ± 1.8 b | 5.3 ± 1.8 a | 4.5 ± 0.6 b |
| Predator | Cantharidae | 0.0 ± 0.0 b | 0.8 ±0.5 b | 7.8 ± 2.0 a | 6.0 ± 2.5 a |
| | Carabidae | 1.8 ± 0.5 b | 4.8 ± 0.8 ab | 1.5 ± 0.6 b | 5.8 ± 1.7 a |
| | Dolichopodidae | 3.8 ± 1.4 b | 5.8 ± 1.7 ab | 8.5 ± 1.5 a | 7.5 ± 1.8 ab |
| | Formicidae | 17.5 ± 7.0 ab | 21.0 ± 3.9 a | 16.8 ± 11.0 ab | 11.3 ± 2.4 b |
| | Linyphiidae | 11.0 ± 3.9 | 10.5 ± 0.6 | 10.0 ± 3.4 | 7.5 ± 1.7 |
| | Staphylinidae | 27.5 ± 4.4 d | 50.0 ± 13.2 c | 74.0 ± 37.3b | 175.8 ± 147.1 a |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Missing letters indicate no significant treatment effects were found. Table consists of families of parasitoids that represent 1% or greater of the total number of natural enemies captured.

***Pitfall Traps***

A total of 12,584 arthropods were collected in pitfall traps over two field studies, and consisted of predators (43%), omnivores (25%), parasitoids (14%), herbivores (10%), and detritivores (8%). The most abundant predators were ants (Formicidae; 57%), wolf spiders (Lycosidae; 15%), and rove beetles (Staphylinidae; 12%). The most abundant omnivore was crickets (Gryllidae; 99%), and the most abundant parasitoids were wasps in the families Scelionidae (87%), Mymaridae (4%), and Ceraphronidae (2%). The most common herbivores collected were sap beetles (Nitidulidae; 59%), dirt-colored seed bugs (Rhyparochromidae; 19%) and burrowing bugs (Cydnidae; 3%). The most common detritivores were scuttle flies (Phoridae; 24%), scarab beetles (Scarabaeidae; 21%), and pleasing fungus beetles (Erotylidae; 13%).

In 2020, a significant effect of treatment on predator species richness was detected ($F_{3,11} = 3.98$, $p = 0.04$), however $p$-value corrections resulting from Tukey pairwise comparisons did not detect any significant differences. Similarly, no differences in predator diversity were detected ($F_{3,11} = 1.60$, $p = 0.25$). Total predator abundance differed by treatment ($\chi^2 = 71.80$, df = 3, $p < 0.001$), with the greatest number of predators occurring in LMRye and the fewest in LMFR (Figure 4-7). Rove beetles ($\chi^2 = 16.31$, df = 3, $p < 0.001$), were more abundant in LMRye compared to the other treatments (Table 4-11), and ants ($\chi^2 = 28.85$, df = 3, $p < 0.001$) were more abundant in LMRye compared to CT and LMFR. In contrast, the spider family, Linyphiidae ($\chi^2 = 12.98$, df = 3, $p < 0.01$) was more abundant in CT compared to LMFR. No treatment differences were detected for the four remaining predator families captured, Carabidae ($\chi^2 = 3.98$, df = 3, $p = 0.26$), Henicopidae ($\chi^2 = 5.37$, df = 3, $p = 0.15$), and Lycosidae ($\chi^2 = 3.81$, df = 3, $p = 0.28$).

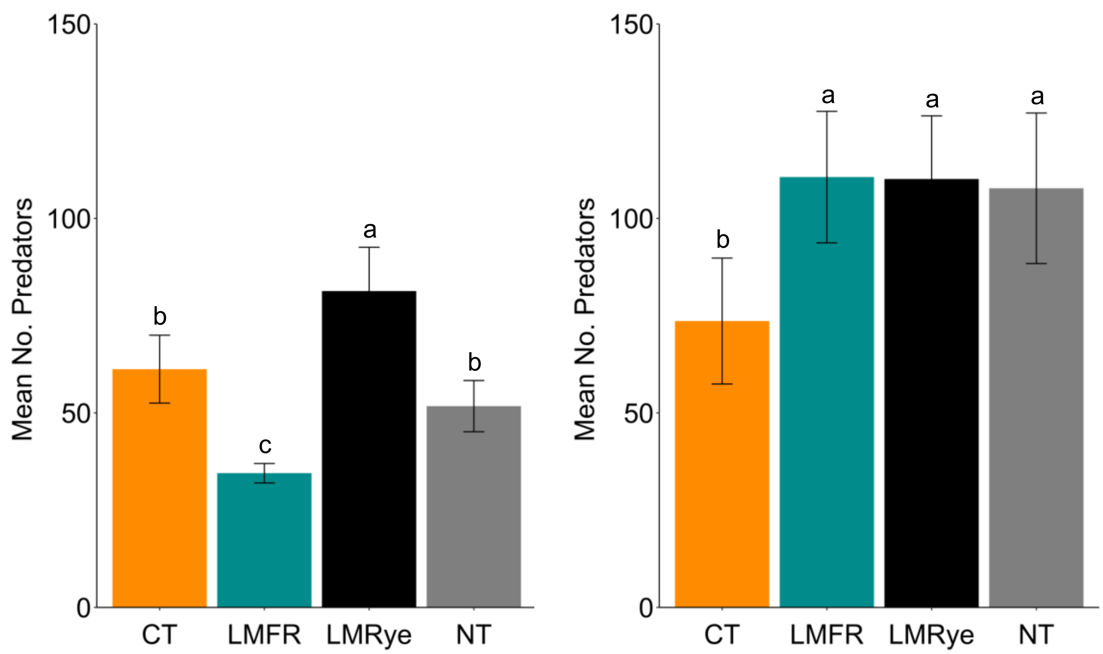


**Figure 4-7.** Mean number of predators collected from pitfall traps in Beltsville, MD in 2020 (left) and 2021 (right). CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Means bearing the same letter are not significantly different at the 5% probability level. Graph consists of families that represent 1% or greater of the total number of predators captured.

In 2021, no differences in predator richness ($F_{3,12} = 0.13$, $p = 0.94$) or diversity ($F_{3,12} = 0.56$, $p = 0.65$) were detected. However, total predator abundance differed among treatments ($\chi^2 = 82.57$, df = 3, $p < 0.001$; Figure 4-7). More predators were detected in all cover crop treatments compared to CT. Soldier beetles (Cantharidae) were more abundant in the living mulch treatments compared to CT and NT ($\chi^2 = 23.54$, df = 3, $p < 0.001$; Table 4-11). Carabid beetles ($\chi^2 = 16.47$, df = 3, $p < 0.001$) were more abundant in LMRye compared to CT and LMFR, and centipedes (Henicopidae) were more abundant in NT compared to CT ($\chi^2 = 9.98$, df = 3, $p = 0.02$). No treatment differences were detected in the abundance of the four predator families, Formicidae ($\chi^2 = 3.57$, df = 3, $p = 0.31$), Linyphiidae ($\chi^2 = 1.23$, df = 3, $p = 0.75$), Lycosidae ($\chi^2 = 1.07$, df = 3, $p = 0.78$), and Staphylinidae ($\chi^2 = 7.2$, df = 3, $p = 0.06$).

**Table 4-11.** Mean number (± SEM) of predators captured from pitfall traps in 2020 and 2021 (Beltsville, MD).

| Family | CT | NT | LMFR | LMRye |
|---|---|---|---|---|
| | | --- 2020 --- | | |
| Carabidae | 10.0 ± 2.5 | 7.5 ± 2.0 | 5.5 ± 1.9 | 11.7 ± 2.3 |
| Formicidae | 23.3 ± 4.7 b | 24.3 ± 2.5 ab | 15.3 ± 1.7 b | 35.7 ± 3.4 a |
| Henicopidae | 3.3 ± 1.3 | 0.8 ± 0.5 | 0.8 ± 0.5 | 2.3 ± 1.3 |
| Linyphiidae | 5.0 ± 1.4 a | 1.5 ± 0.6 ab | 0.8 ± 0.5 b | 2.3 ± 1.3. ab |
| Lycosidae | 15.5 ± 5.0 | 12.5 ± 4.2 | 5.3 ± 0.8 | 7.0 ± 2.5 |
| Staphylinidae | 4.0 ± 1.7 b | 6.0 ± 2.6. b | 7.0 ± 1.2. b | 22.7 ± 4.9 a |
| | | --- 2021 --- | | |
| Cantharidae | 0.5 ± 0.3 b | 0.8 ± 0.5 b | 7.6 ± 2.4 a | 5.8 ± 2.7 a |
| Carabidae | 4.0 ± 0.9 b | 6.5 ± 1.1 ab | 2.3 ± 0.9 b | 10.6 ± 2.6 a |
| Formicidae | 55.0 ± 13.0 | 76.4 ± 19.5 | 83.6 ± 3.8 | 52.8 ± 14.4 |
| Henicopidae | 0.8 ± 0.3 b | 3.4 ± 0.9 a | 1.0 ± 0.4 ab | 1.8 ± 0.9 ab |
| Linyphiidae | 3.1 ± 0.5 | 4.6 ± 0.6 | 3.5 ± 0.8 | 4.1 ± 1.7 |
| Lycosidae | 5.9 ± 1.1 | 7.5 ± 4.2 | 5.6 ± 1.1 | 5.9 ± 1.1 |
| Staphylinidae | 6.0 ± 1.1 | 10.4 ± 1.6 | 9.8 ± 2.8 | 21.5 ± 7.9 |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Missing letters indicate no significant treatment effects were found. Means bearing the same letter are not significantly different at the 5% probability level between treatments within each experiment year. Table consists of families of predators and parasitoids that represent 1% or greater of the total number of natural enemies captured.

***Pollinator Richness and Visitation***

A total of 1,116 pollinators representing 34 species within 14 genera and 4 families were collected in bee bowl traps. The most common species collected were *Melissodes bimaculatus* (40%), *Agapostemon virescens* (10%), *Lasioglossum pilosum* (10%), and *Eucera hamata* (6%). In 2020, no differences in pollinator species richness ($F_{3,11} = 0.60$, $p = 0.63$) were found in bowl traps set at the height of clover flowers. Similarly, no differences in richness ($F_{3,11} = 0.33$, $p = 0.80$) were found in bowl traps set between VT (tassel) and R1 (first silk) stage sweet corn. The abundance of one species, *Lasioglossum ligatus/poeyi* was impacted by treatment ($\chi^2 = 8.47$, df = 3, $p = 0.04$), with more individuals collected in LMFR compared to NT (Table 4-12). The remaining eight species whose abundance made up at least 2% of all pollinators collected did not differ between treatments ($p > 0.05$). Similar to 2020, no differences in species richness were detected in bowl traps set at the height of the clover ($F_{3,12} = 0.27$, $p = 0.85$) or at varying heights within the flowering sweet corn ($F_{3,12} = 0.53$, $p = 0.67$) in 2021. No species making up greater than 2% of the total abundance were impacted by treatment ($p > 0.05$; Table 4-12) in 2021.

**Table 4-12.** Mean number (± SEM) of pollinators captured from bee bowl traps in 2020 and 2021 (Beltsville, MD).

| Family | Species | CT | NT | LMFR | LMRye |
|---|---|---|---|---|---|
| | | --- 2020 --- | | | |
| Apidae | *Mellisodes bimaculatus* | 14.5 ± 4.7 | 9.5 ± 1.9 | 11.8 ± 2.3 | 17.0 ± 6.3 |
| | *Eucera. hamata* | 6.5 ± 1.9 | 3.0 ± 1.1 | 4.8 ± 2.4 | 2.3 ± 1.3 |
| Halictidae | *Augochlora pura* | 1.0 ± 0.6 | 1.3 ± 0.5 | 1.3 ± 0.8 | 1.3 ± 0.5 |
| | *Agapostemon texanus* | 0.8 ± 0.5 | 0.8 ± 0.3 | 2.5 ± 1.5 | 0.3 ± 0.3 |
| | *Agapostemon virescens* | 3.3 ± 0.8 | 5.8 ± 1.8 | 2.8 ± 0.3 | 3.3 ± 1.1 |
| | *Lasioglossum bruneri* | 0.3 ± 0.3 | 0.3 ± 0.3 | 1.0 ± 0.4 | 1.0 ± 0.6 |
| | *Lasioglossum leucocomus* | 0.8 ± 0.3 | 1.0 ± 0.4 | 1.5 ± 1.0 | 1.3 ± 0.9 |
| | *Lasioglossum ligatus/poeyi* | 0.5 ± 0.3 ab | 0.3 ± 0.3 b | 1.8 ± 0.5 a | 1.3 ± 0.6 ab |
| | *Lasioglossum parallelus* | 0.3 ± 0.3 | 2.0 ± 1.1 | 0.3 ± 0.3 | 0.8 ± 0.5 |
| | *Lasioglossum pilosum* | 3.0 ± 0.7 | 2.8 ± 1.1 | 7.5 ± 3.8 | 5.0 ± 1.8 |
| | | --- 2021 --- | | | |
| Apidae | *Mellisodes bimaculatus* | 21.3 ± 5.3 | 13.3 ± 2.2 | 16.0 ± 3.9 | 9.0 ± 3.4 |
| | *Apis mellifera* | 4.0 ± 0.9 | 2.8 ± 0.3 | 2.3 ± 0.9 | 3.0 ± 2.0 |
| Halictidae | *Augochlora pura* | 2.0 ± 0.7 | 1.5 ± 0.9 | 2.0 ± 1.1 | 2.0 ± 0.6 |
| | *Agapostemon splendens* | 1.3 ± 0.3 | 2.5 ± 0.5 | 2.0 ± 0.4 | 1.5 ± 0.5 |
| | *Agapostemon texanus* | 1.5 ± 1.0 | 1.8 ± 1.0 | 4.5 ±1.6 | 2.0 ± 0.7 |
| | *Agapostemon virescens* | 7.3 ± 2.2 | 8.0 ± 0.7 | 4.8 ± 1.1 | 5.8 ± 2.3 |
| | *Lasioglossum bruneri* | 2.8 ± 1.1 | 0.5 ± 0.5 | 1.5 ± 0.5 | 1.3 ± 0.5 |
| | *Lasioglossum leucocomus* | 1.8 ± 0.5 | 1.0 ± 0.4 | 2.3 ± 0.8 | 1.5 ± 0.6 |
| | *Lasioglossum ligatus/poeyi* | 1.5 ± 0.9 | 1.0 ± 0.0 | 1.5 ± 0.9 | 1.0 ± 0.6 |
| | *Lasioglossum pilosum* | 6.3 ± 1.9 | 6.0 ± 1.3 | 11.3 ± 3.0 | 5.5 ± 1.9 |

CT indicates conventional till, NT is no-till (NT), LMFR indicates living mulch + forage radish residue and LMRye signifies living mulch + rye residue. Missing letters indicate no significant treatment effects were found. Means bearing the same letter are not significantly different at the 5% probability level. Table consists of bee species that represent 2% or greater of the total number captured.

Visual observations revealed similar groups of pollinators utilizing red clover flowers in living mulch treatments during 2020 and 2021. As such, data was combined to better quantify overall pollinator visitation. The most common hymenopteran pollinators observed were bumble bees (*Bombus spp.*), honeybees (*Apis mellifera*), carpenter bees (*Xylocopa virginica*) and individuals classified as "large dark bees" (Figure 4-8). The most common lepidopteran pollinators observed visiting red clover flowers were skippers (Family: Hesperiidae), whites/sulfurs (Family: Pieridae), brushfoots (Family: Nymphalidae), and gossamer-winged butterflies (Family: Lycaenidae; Figure 4-8). Monarch and swallowtail butterflies were infrequently observed feeding on red clover and no bees categorized as metallic bees or small dark bees were observed feeding on red clover flower.

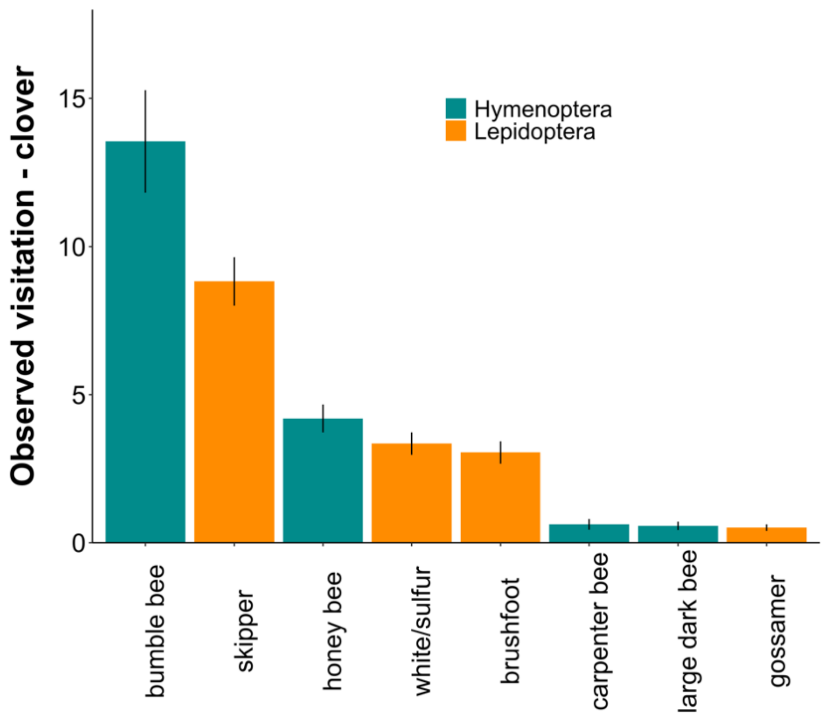


**Figure 4-8.** Mean number of pollinators observed visiting red clover flowers over a 20-minute period (10 minutes in late-morning and 10 minutes in mid-afternoon) in Beltsville, MD in 2020 and 2021.

The most common pollinators observed visiting sweet corn tassel in 2020 and 2021 were categorized as honey bees, large dark bees, and metallic bees. No observations of large carpenter bees, long-horned bees, bumble bees or those categorized as small dark bees were made. No differences in total pollinator visitation to sweet corn tassels were detected between treatments ($\chi^2 = 0.98$, df = 3, $p = 0.81$). Further, visitation occurrences of the most commonly encountered pollinators did not differ between treatments ($p > 0.05$; Figure 4-9).

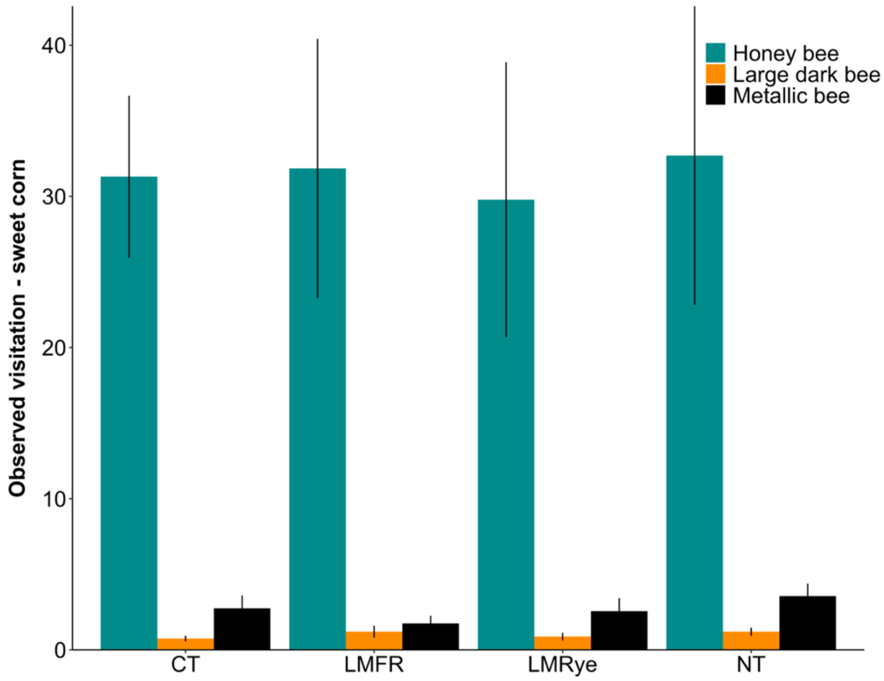


**Figure 4-9.** Mean number of pollinators observed visiting sweet corn tassels over a 20-minute period (10 minutes in late-morning and 10 minutes in mid-afternoon) in Beltsville, MD in 2020 and 2021.

## Discussion

The primary objective of this study was to assess the impact of an interplanted red clover living mulch and/or cover crop residue on beneficial arthropods (natural enemies and pollinators) in sweet corn. While the total abundance of natural enemies was not significantly altered, several groups in natural enemies were affected. In addition to this, both red clover and flowering sweet corn was used as a food source by various pollinators. Sticky card and pitfall trap data indicated that the total abundance of predators and parasitoids was similar across all treatments during most sampling events, with the exception of greater total predator abundance detected in pitfall traps in all cover crop treatments compared to CT during one study year and some inconsistent differences detected from sticky cards during specific sample dates. In contrast, emergence trap data indicated that by the end of the sweet corn growing season, the total abundance of predators and parasitoids was greater in all cover crop treatments (NT, LMFR and LMRye) compared to CT. As such, these findings partially support our hypothesis that there would be an increased number of natural enemies in cover crop diversified treatments. Sticky card results indicated that several families of parasitoids and predators representing multiple taxa were positively impacted by the presence of red clover; and one family of hyperparasitoids was less abundant in plots with red clover. Natural enemy responses to the NT treatment which consisted solely of cover crop residue were mostly more similar to the conventional till (CT) than the red clover systems during the sweet corn growing season. Following harvest, emergence cage data also showed that several families of predators and parasitoids were more abundant in red clover treatments compared to CT and NT. Additionally, several families of predators and parasitoids were more abundant in the NT treatment compared to CT.  Altogether, this indicates that the abundance of several groups of natural enemies can be manipulated by incorporating red clover living mulch and/or cover crop residue into sweet corn production. Further, several groups of pollinators were observed utilizing red clover as a food source, suggesting the inclusion of red clover in annual crops can be used to make these habitats more hospitable to pollinators.

The addition of a flowering living mulch can alter the microhabitat within cropping systems by providing beneficial arthropods with important resources such as nectar, pollen and alternative prey as well as refuge (Gaudin et al., 2013; Morrison, 1961). In this study, more *Geocoris* sp., were captured on sticky traps in plots interplanted with red clover (LMFR and LMRye) compared to CT and NT treatments. Similarly, Kahl et al. (2019) discovered more *Geocoris* spp., in cucumber interplanted with red clover living mulch compared to monoculture cucumber plots. Another study investigating the effect of interplanted sunflower (*Helianthus* spp.) strips on natural enemies in sweet corn, tomatoes, collards (*Brassica oleracea* var. *viridis*), okra (*Abelmoschus esculentus*), and watermelon (*Citrullus lanatus*) found more *Geocoris* spp., on all crops adjacent to sunflower strips compared to the same crop in control treatments (Jones & Gillett, 2005). *Geocoris* spp., are considered effective predators of numerous crop pests including aphids (Aphididae), thrips (Thripidae), armyworms (Noctuidae), etcetera (Kóbor, 2020). *Geocoris* spp., have also been identified as key predators of *Helicoverpa zea* in cotton (Torres & Ruberson, 2006) and soybean (A. C. Anderson & Yeargan, 1998). *H. zea* is among the most damaging and difficult to control insect pests of sweet corn (Olmstead et al., 2016). As such, increases in *Geocoris* spp., in sweet corn systems may contribute to increased predation of *H. zea* eggs.

Similar to *Geocoris* spp., trichogrammatid wasps can contribute markedly to the natural control of a profusion of insect pest populations; and more trichogrammatid wasps were captured on sticky cards in plots interplanted with red clover (LMFR and LMRye) compared to CT and NT treatments. The longevity and parasitism rate of the egg parasitoid, *Trichogramma atopovirilia* Oatman & Platner was increased in the presence of red clover (Díaz et al. 2012). As such, red clover flowers may have attracted Trichogrammatid wasps by serving as a nutrient source consequently leading to greater number of visitors in plots with red clover. Trichogrammatid wasps are also effective egg parasitoids of *H. zea* and other economically important lepidopteran pests (Hoffmann et al., 1990; Smith, 1996). Manandhar and Wright (2016) interplanted sweet corn with cowpea (*Vigna unguiculata*) and sunn hemp (*Crotolaria juncea*) living mulches and found increased parasitism of *H. zea* eggs by *Trichogramma* spp., compared to monoculture sweet corn. This increase was attributed primarily to a greater abundance of alternate host eggs in diversified corn plantings. In contrast to Trichogrammatids, fewer Ceraphronid wasps were captured on sticky cards in both red clover treatments compared to CT each study year. Little is known about this group of parasitic wasps. However, several species are hyperparasitoids known to negatively impact biological control efforts are in this family (N. F. Johnson, 2009).

Unlike *Geocoris* spp., and the wasp families Trichogrammatidae and Ceraphronidae, some wasp families response to red clover treatments were inconsistent according to sticky card results. In 2019, higher numbers of parasitoid wasps in the families Encyrtidae, Figitidae and Scelionidae were captured in red clover treatments compared to CT and NT. In 2020, greater number of wasps in the family Platygastridae was captured in LMRye compared to CT, and more Scelionid wasps were captured in LMFR compared to CT. Previous research investigating natural enemy abundance in floral diversified crops has also shown mixed results. In some instances, the addition of flowering plants can act as a sink, resulting in lower numbers of natural enemies in crop rows neighboring flowering plants (Hunt et al., 2021; Sedlacek et al., 2012; V. Johnson et al., 2023).

Previous research investigating the effects of increased plant diversity and/or terminated residues has generally found more epigeal predators in diversified crop plantings compared to bare-ground treatments (Clark et al., 1993; Prasifka et al., 2006). In the current study, more epigeal predators were only detected in cover crop treatments (LMFR, LMRye and NT) compared to CT in 2021; and in 2020, total predator abundance was greater only in LMRye compared with CT. Staphylinidae, Carabidae, and Formicidae are families of epigeal predators reported to be enhanced by increased amounts of plant coverage (Miguel A. Altieri et al., 1985; Prasifka et al., 2006; Rivers et al., 2017). During the current study, pitfall trap captures indicated that these families were more abundant in at least one cover crop treatment each study year. Analogously, emergence trap data indicated higher numbers of Carabidae and Staphylinidae in at least one cover crop treatment in 2020 and 2021. More Carabidae were found also in pitfall traps in LMRye compared to LMFR and CT in 2021.

In 2021, pitfall traps and emergence cages captured greater numbers of Cantharidae in both red clover treatments compared to CT and NT. Cantharidae are a group of omnivorous beetles commonly found on flowers, where adults feed on insects, nectar and pollens (Pelletier & Hébert, 2014).

Fewer Linyphiidae were captured in pitfall traps in 2020 in LMFR compared to CT and no difference existed among treatments in the number of spiders from the family Lycosidae. Lycosid spiders were not captured in emergence cages and Linyphiidae response to treatment varied between study years. In 2020, more Linyphiid spiders were found in emergence cages in LMFR compared to CT, however no treatment differences were detected in 2021. A study investigating the response of generalist predators in reduced-tillage corn found similar numbers of both spider families in spring disked and untilled treatments with cover crop residues (Clark et al., 1993). Contrary to these findings, higher numbers of Lycosid spiders were found in Chinese cabbage (*Brassica chinensis*) intercropped with either green cabbage (*Brassica oleracea*), garlic (*Allium sativum*) or lettuce (*Lactuca sativa*) compared to monoculture Chinese cabbage (Hongjiao et al. 2010). In another study, the abundance of spiders, including those in the families Lycosidae and Linyphiidae was greater in vegetable plots containing clover or weedy background vegetation compared to clean, cultivated plots (Miguel A. Altieri et al., 1985).

In addition to the aforementioned groups of beneficial arthropods, some pollinator groups were also attracted to red clover plots. Observations of hymenopteran and lepidopteran pollinator visitation suggested that *Bombus* spp. were the most frequent pollinator visitors to red clover flowers during the observation periods, followed by Hesperiidae, *Apis mellifera*, Pieridae and

Nymphalidae. Visual observations of sweet corn tassels revealed that *A. mellifera* were noticeably the most frequent pollinators utilizing sweet corn pollen. Large dark bees (*Mellisodes bimaculatus*) and metallic bees, likely *Agapostemon* spp. and *Augochlora* spp., were also observed collecting pollen from sweet corn tassels. Across all treatments, *M. bimaculatus*, *A. virescens,* and *Lasioglossum* in the subgenus (*Dialictus*) were the most abundant species captured in bowl traps. However, these species were rarely observed visiting red clover flowers; and numbers captured were similar among treatments suggesting their association was with corn pollen.

A study cataloguing insect pollinators in Iowa cornfields also identified *M. bimaculatus*, *A. virescens,* and *Lasioglossum* in the subgenus (*Dialictus*) as abundant bees captured in similarly-designed bowl traps (Wheelock & O'Neal, 2016). Further, Danner et al. (2014) confirmed a strong association between *A. mellifera* and corn pollen, showing corn to be an intensively used pollen resource for *A. mellifera* colonies regardless of the availability of alternative pollen sources. A strong association between *M. bimaculatus* and corn pollen has also been observed, While densities of *A. mellifera* and other select bee species may be greater in cornfields, recent research investigating the impact of mass-flowering pollinator-independent crops, such as corn, on wild bee abundance has shown that increased cultivation of these crops results in lower densities of *Bombus* spp., within crop fields and the surrounding landscape (Holzschuh et al., 2016).

In this study, *Bombus* spp., *A. mellifera, Xylocopa virginica,* and bees classified as "large dark bees" were observed foraging in red clover flowers. Of these, *X. virginica* and *Bombus* spp. were solely observed visiting red clover flowers and *Bombus* spp. were detected visiting red clover more than any other pollinator group. Red clover flowers have long been recognized for their ability to attract foraging *Bombus* spp., including rare and declining species (Carvell et al. 2006, Goulson et al. 2005, Rundlöf et al. 2014, Wermuth and Dupont 2010). In addition, red clover can positively influence *Bombus* spp., reproduction as there are greater densities of queens and male bees occurring in landscapes containing red clover fields compared to those without (Rundlöf et al., 2014). As such, incorporating red clover plants into pollinator-independent crops such as sweet corn may help support populations of *Bombus* spp. Further, the incorporation of red clover into insect-pollinated crops may increase pollination services and subsequent crop yields. *Bombus* spp. are generally recognized as efficient pollinators of numerous field and vegetable crops. Consequently, efforts are often directed at increasing their abundance in field and greenhouse production systems (Nayak et al., 2020). Research investigating floral diversification in insect-pollinated crops has shown that greater bee abundance, including *Bombus* spp., can result in increased crop yields (Blaauw & Isaacs, 2014; Garibaldi et al., 2014). Despite the high numbers of foraging *Bombus* spp. observed in red clover plots in this study, they were rarely captured in bee bowl traps. Recent research comparing pollinator sampling methods identified bowl traps as less effective at capturing *Bombus* spp. than other trapping methods (Bell et al., 2023). This suggests that red clover's impact on *Bombus* spp. number and richness may have been significantly underestimated from bowl trap data. Even so, this research supports our hypothesis that incorporating red clover into annual crops can provide resources for pollinators.

Apart from honeybees and to a lesser extent *M. bimaculatus*, which were observed in all systems, variation in pollinator groups foraging in flowering sweet corn and red clover suggests that these plants provide food resources to two distinct communities of pollinators. Sweet corn, which provides only pollen, was utilized primarily by honeybees and a variety of solitary bee species including those in the genera Agapostemon, Augoclora, and Augochlorella. In contrast, red clover flowers were utilized mainly by *Bombus* spp. and *X. virginica.*

In general, it is difficult to predict how an increase in beneficial arthropods as a result of enhanced plant diversification will impact their services and crop yield in agroecosystems (Begg et al., 2017). Irrespective of this, recent declines in insect abundance have been attributed, in part, to habitat loss resulting from increased acreage of annual crops (Sánchez-Bayo & Wyckhuys, 2019). This study provides evidence that increasing in-field plant diversity through the inclusion of a perennial flowering cover crop can be used to support insect natural enemies and foraging pollinators. Nevertheless, additional research is needed to better understand the conservation benefits of incorporating red clover into sweet corn and other cropping systems, as well as to identify any potential benefits of enhanced natural enemy activity and pollinator foraging on crop productivity. Though these responses were not consistent across experiment years, the overall findings generally support our hypothesis that red clover living mulch can be used to augment and conserve beneficial arthropods in sweet corn plantings.

## Practical Implications

Results of this investigation indicated that the novel cover cropping tactic of combining a living mulch (red clover) with cover crop residue can effectively suppress weeds and simultaneously augment some beneficial arthropods (natural enemies and pollinators) in sweet corn plantings. Further, under ideal growing conditions, this system has the potential to be as profitable as traditional sweet corn production methods. However, several drawbacks or barriers to adopting this system remains. For example, despite an increase in some beneficial arthropods in the cover cropping system, further pest control methods are needed to prevent ears from being infested with herbivorous insects. Specific equipment is also required if the cover crop rows are to be planted at an inter-row spacing of 15.2 cm as used in this experiment, and therefore may require an initial investment in new planting equipment before on-farm implementation. In addition, sweet corn production using non-transgenic varieties typically requires multiple insecticide applications for corn earworm control. These insecticide applications could be detrimental to pollinators foraging red clover flowers as well as natural enemies that are attracted to the cover crop diversified sweet corn plantings. As such, the red clover living mulch + cover crop residue systems investigated during this experiment will be more hospitable to beneficials arthropods in transgenic sweet corn production, where significantly fewer or no insecticide applications are required. To this point, relatively high acreage of transgenic sweet corn is grown in the Mid-Atlantic region. As such, the red clover living mulch system is compatible to this region and thus could be used to help restore vital resources needed by beneficial arthropods on a large scale.

This experiment showed that the living and dying mulch cover crop systems investigated can provide similar level of weed suppression when implemented alone or in combination with banded residual herbicides. However, the low cost of herbicides relative to overall production costs combined with the observed variability in net profit between herbicide treated and untreated systems suggests that profits may be more reliably maintained when residual herbicides are used. Still, the adoption of the living mulch systems investigated could result in a 50% or greater reduction in the amount of herbicide entering the environment as herbicides are applied only within the sweet corn row as opposed to throughout the entire field.

Future research should investigate the compatibility of the cover crop systems investigated in other vegetable crops, especially those with different pest complexes and reliant on insect pollination. It is possible that increased pollinator abundance resulting from the presence of the interplanted red clover would increase pollination, and ultimately yield, in some insect pollinated crops. Further, the increase in certain families of insect predators and parasitoids observed during the study may result in higher levels of herbivorous pest suppression. Additional research is also needed to best determine how to reliably maintain crop yields in the living mulch systems investigated without losing the pest suppression benefits that they provide.

## Appendix A: Supplemental Materials for Chapter Three

**Table S1. Breakdown of inputs used in economic analysis**

| INPUTS | UNIT | PRICE |
|---|---|---|
| **YEAR** | | |
| **INCOME** | | |
| SWEET CORN | DOZEN | $6.26 |
| | | |
| **EXPENSES** | | |
| **SEED** | | |
| SWEET CORN | 1,000 SEEDS | $18.63 |
| CEREAL RYE | KG | $2.34 |
| RADISH | KG | $3.33 |
| RED CLOVER | KG | $9.33 |
| CRIMSON CLOVER | KG | $6.33 |
| **FERTILIZER** | | |
| NITROGEN | KG | $1.53 |
| SULFATE | KG | $2.00 |
| **PESTICIDES** | | |
| ATRAZINE | LITER | $6.37 |
| DUAL II MAGNUM | LITER | $17.00 |
| CROP OIL CONCENTRATE | LITER | $15.80 |
| **OTHER** | | |
| SOIL TEST | HECTARE | $3.06 |
| CROP INSURANCE - Corn | HECTARE | $49.99 |
| DRYING FUEL AND HANDLING | TONNE | $14.00 |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | $3.06 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | $24.71 |
| **FIXED COSTS - 2023 Custom Rates** | | |
| STALK CHOPPING | HECTARE | $50.04 |
| CHISEL PLOWING | HECTARE | $51.37 |
| DISKING | HECTARE | $25.39 |
| FIELD CULTIVATOR/FINISHER | HECTARE | $45.64 |
| VERTICAL TILLAGE | HECTARE | $48.11 |
| MOWING | HECTARE | $54.94 |
| ROLLER CRIMPER | HECTARE | $40.77 |
| FERTILIZER SPREADING | HECTARE | $23.60 |
| SIDEDRESSING | HECTARE | $28.69 |
| PESTICIDE SPRAYING | HECTARE | $25.94 |
| NOTILL DRILLING | | |
| SMALL GRAIN | HECTARE | $57.90 |
| PLANTING | | |
| CORN - Conventional | HECTARE | $55.45 |
| CORN - NoTill | HECTARE | $58.84 |
| BROADCAST SEEDING SMGRAIN | HECTARE | $27.68 |
| HARVESTING | | |
| CORN | HECTARE | $92.84 |
| HAULING | TONNE | $8.00 |
| IRRIGATION PAYMENT | HECTARE | $371.00 |
| LAND CHARGE | HECTARE | $309.00 |

**Table S2. Income, Variable Costs and Fixed Costs : CT 2020**

| SWEET CORN, CT - PER HECTARE 2020 | | | | Herbicide | No Herbicide |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN,CT 2020, HERBICIDE REP 1 | DOZEN | 3274 | $6.26 | $20,495.24 | |
| SWEET CORN,CT 2020, HERBICIDE REP 2 | DOZEN | 3184 | $6.26 | $19,931.84 | |
| SWEET CORN,CT 2020, HERBICIDE REP 3 | DOZEN | 3992 | $6.26 | $24,989.92 | |
| SWEET CORN,CT 2020, HERBICIDE REP 4 | DOZEN | 1659 | $6.26 | $10,385.34 | |
| SWEET CORN, CT 2020, NO HERBICIDE REP 1 | DOZEN | 3229 | $6.26 | | $20,213.54 |
| SWEET CORN, CT 2020, NO HERBICIDE REP 2 | DOZEN | 2781 | $6.26 | | $17,409.06 |
| SWEET CORN, CT 2020, NO HERBICIDE REP 3 | DOZEN | 3274 | $6.26 | | $20,495.24 |
| SWEET CORN, CT 2020, NO HERBICIDE REP 4 | DOZEN | 1166 | $6.26 | | $7,299.16 |
| **VARIABLE COSTS** | | | | | |
| CRIMSON CLOVER | KG | 1.36 | $6.33 | $8.61 | $8.61 |
| CEREAL RYE | KG | 25.4 | $2.34 | $59.44 | $59.44 |
| RADISH | KG | 1.59 | $3.33 | $5.29 | $5.29 |
| SEED - PROVIDENCE | 1000 SEEDS | 49 | $18.63 | $912.87 | $912.87 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE | LITER | 1.18 | $6.37 | $7.52 | - |
| DUAL II MAGNUM | LITER | 0.71 | $17.00 | $12.07 | - |
| CROP OIL CONCENTRATE | LITER | 1.42 | $15.80 | $22.44 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $53.28 | $51.49 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $3,113.94 | $3,070.13 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| MOWING | HECTARE | 1 | $54.94 | $54.94 | $54.94 |
| DISKING | HECTARE | 1 | $25.39 | $25.39 | $25.39 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS | HECTARE | 1 | $25.94 | $25.94 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $10.59 | $9.49 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $718.75 | $691.71 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,832.69 | $3,761.84 |
| NET PROFIT REP 1 | | | | $16,099.15 | $15,606.60 |
| NET PROFIT REP 2 | | | | $16,380.85 | $13,083.82 |
| NET PROFIT REP 3 | | | | $14,415.21 | $19,544.14 |
| NET PROFIT REP 4 | | | | $18,346.49 | $19,544.14 |

Assumptions:

No other post harvest or marketing expenses included

**Table S3. Income, Variable Costs and Fixed Costs : NT 2020**

| SWEET CORN, NT - PER HECTARE 2020 | | | | Herbicide | No Herbicide |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN,NT 2020, HERBICIDE REP 1 | DOZEN | 2512 | $6.26 | $15,725.12 | |
| SWEET CORN,NT 2020, HERBICIDE REP 2 | DOZEN | 2287 | $6.26 | $14,316.62 | |
| SWEET CORN,NT 2020, HERBICIDE REP 3 | DOZEN | 2512 | $6.26 | $15,725.12 | |
| SWEET CORN,NT 2020, HERBICIDE REP 4 | DOZEN | 2781 | $6.26 | $17,409.06 | |
| SWEET CORN, NT 2020, NO HERBICIDE REP 1 | DOZEN | 2915 | $6.26 | | $18,247.90 |
| SWEET CORN, NT 2020, NO HERBICIDE REP 2 | DOZEN | 3050 | $6.26 | | $19,093.00 |
| SWEET CORN, NT 2020, NO HERBICIDE REP 3 | DOZEN | 1973 | $6.26 | | $12,350.98 |
| SWEET CORN, NT 2020, NO HERBICIDE REP 4 | DOZEN | 1659 | $6.26 | | $10,385.34 |
| **VARIABLE COSTS** | | | | | |
| CRIMSON CLOVER | KG | 1.36 | $6.33 | $8.61 | $8.61 |
| CEREAL RYE | KG | 25.4 | $2.34 | $59.44 | $59.44 |
| RADISH | KG | 1.59 | $3.33 | $5.29 | $5.29 |
| SEED - PROVIDENCE | 1000 SEEDS | 49 | $18.63 | $912.87 | $912.87 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE | LITER | 1.18 | $6.37 | $7.52 | - |
| DUAL II MAGNUM | LITER | 0.71 | $17.00 | $12.07 | - |
| CROP OIL CONCENTRATE | LITER | 1.42 | $15.80 | $22.44 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $53.28 | $51.49 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $3,113.94 | $3,070.13 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| ROLLER CRIMPER | HECTARE | 1 | $40.77 | $40.77 | $40.77 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS | HECTARE | 1 | $25.94 | $25.94 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $8.91 | $7.81 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $677.51 | $650.47 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,791.45 | $3,720.59 |
| NET PROFIT REP 1 | | | | $11,933.67 | $14,527.31 |
| NET PROFIT REP 2 | | | | $10,525.17 | $15,372.41 |
| NET PROFIT REP 3 | | | | $11,933.67 | $8,630.39 |
| NET PROFIT REP 4 | | | | $13,617.61 | $6,664.75 |

Assumptions:

No other post harvest or marketing expenses included

**Table S4. Income, Variable Costs and Fixed Costs : LMFR 2020**

| SWEET CORN, LMFR - PER HECTARE 2020 | | | | Herbicide | No Herbicide |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN, LMFR 2020, HERBICIDE REP 1 | DOZEN | 3005 | $6.26 | $18,811.30 | |
| SWEET CORN, LMFR 2020, HERBICIDE REP 2 | DOZEN | 3453 | $6.26 | $21,615.78 | |
| SWEET CORN, LMFR 2020, HERBICIDE REP 3 | DOZEN | 3588 | $6.26 | $22,460.88 | |
| SWEET CORN, LMFR 2020, HERBICIDE REP 4 | DOZEN | 3543 | $6.26 | $22,179.18 | |
| SWEET CORN, LMFR 2020, NO HERBICIDE REP 1 | DOZEN | 3050 | $6.26 | | $19,093.00 |
| SWEET CORN, LMFR 2020, NO HERBICIDE REP 2 | DOZEN | 3543 | $6.26 | | $22,179.18 |
| SWEET CORN, LMFR 2020, NO HERBICIDE REP 3 | DOZEN | 3139 | $6.26 | | $19,650.14 |
| SWEET CORN, LMFR 2020, NO HERBICIDE REP 4 | DOZEN | 2646 | $6.26 | | $16,563.96 |
| **VARIABLE COSTS** | | | | | |
| RED CLOVER | KG | 6.8 | $9.33 | $63.44 | $63.44 |
| RADISH | KG | 4.54 | $3.33 | $15.12 | $15.12 |
| SEED - PROVIDENCE | 1000 SEEDS | 20 | $18.63 | $372.60 | $372.60 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE (.5ac) | QUART | 0.625 | $6.37 | $3.98 | - |
| DUAL II MAGNUM (.5ac) | QUART | 0.375 | $17.00 | $6.38 | - |
| CROP OIL CONCENTRATE (.5ac) | QUART | 0.75 | $15.80 | $11.85 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $29.69 | $28.75 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $2,535.49 | $2,512.34 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| ROLLER CRIMPER | HECTARE | 1 | $40.77 | $40.77 | $40.77 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS (.5ac) | HECTARE | 1 | $12.97 | $12.97 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $8.36 | $7.81 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $663.99 | $650.47 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,199.48 | $3,162.81 |
| NET PROFIT REP 1 | | | | $15,611.82 | $15,930.19 |
| NET PROFIT REP 2 | | | | $15,880.81 | $16,504.03 |
| NET PROFIT REP 3 | | | | $19,261.40 | $16,487.33 |
| NET PROFIT REP 4 | | | | $18,979.70 | $13,401.15 |

Assumptions:

No other post harvest or marketing expenses included

.5ac is the application on a half acre of the plot (herbicide banded)

**Table S5. Income, Variable Costs and Fixed Costs : LMRye 2020**

| **SWEET CORN, LMRye - PER HECTARE 2020** | | | | **Herbicide** | **No Herbicide** |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN, LMRye 2020, HERBICIDE REP 1 | DOZEN | 3005 | $6.26 | $18,811.30 | |
| SWEET CORN, LMRye 2020, HERBICIDE REP 3 | DOZEN | 2332 | $6.26 | $14,598.32 | |
| SWEET CORN, LMRye 2020, HERBICIDE REP 4 | DOZEN | 3095 | $6.26 | $19,374.70 | |
| SWEET CORN, LMRye 2020, NO HERBICIDE REP 1 | DOZEN | 3409 | $6.26 | | $21,340.34 |
| SWEET CORN, LMRye 2020, NO HERBICIDE REP 3 | DOZEN | 2556 | $6.26 | | $16,000.56 |
| SWEET CORN, LMRye 2020, NO HERBICIDE REP 4 | DOZEN | 2781 | $6.26 | | $17,409.06 |
| **VARIABLE COSTS** | | | | | |
| RED CLOVER | KG | 3.63 | $9.33 | $33.87 | $33.87 |
| CEREAL RYE | KG | 30.39 | $2.34 | $71.11 | $71.11 |
| SEED - PROVIDENCE | 1000 SEEDS | 20 | $18.63 | $372.60 | $372.60 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE (.5ac) | QUART | 0.625 | $6.37 | $3.98 | - |
| DUAL II MAGNUM (.5ac) | QUART | 0.375 | $17.00 | $6.38 | - |
| CROP OIL CONCENTRATE (.5ac) | QUART | 0.75 | $15.80 | $11.85 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $30.82 | $29.87 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $2,563.03 | $2,539.88 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| ROLLER CRIMPER | HECTARE | 1 | $40.77 | $40.77 | $40.77 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS (.5ac) | HECTARE | 1 | $12.97 | $12.97 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $8.36 | $7.81 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $663.99 | $650.47 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,227.02 | $3,190.35 |
| NET PROFIT REP 1 | | | | $15,584.28 | $18,149.99 |
| NET PROFIT REP 3 | | | | $11,371.30 | $12,810.21 |
| NET PROFIT REP 4 | | | | $16,147.68 | $14,218.71 |

Assumptions:

No other post harvest or marketing expenses included

.5ac is the application on a half acre of the plot (herbicide banded)

**Table S6. Income, Variable Costs and Fixed Costs : CT 2021**

| SWEET CORN, CT - PER HECTARE 2021 | | | | Herbicide | No Herbicide |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN,CT 2021, HERBICIDE REP 1 | DOZEN | 3184 | $6.26 | $19,931.84 | |
| SWEET CORN,CT 2021, HERBICIDE REP 2 | DOZEN | 3229 | $6.26 | $20,213.54 | |
| SWEET CORN,CT 2021, HERBICIDE REP 3 | DOZEN | 2915 | $6.26 | $18,247.90 | |
| SWEET CORN,CT 2020, HERBICIDE REP 4 | DOZEN | 3543 | $6.26 | $22,179.18 | |
| SWEET CORN, CT 2021, NO HERBICIDE REP 1 | DOZEN | 3094 | $6.26 | | $19,368.44 |
| SWEET CORN, CT 2021, NO HERBICIDE REP 2 | DOZEN | 2691 | $6.26 | | $16,845.66 |
| SWEET CORN, CT 2021, NO HERBICIDE REP 3 | DOZEN | 3723 | $6.26 | | $23,305.98 |
| SWEET CORN, CT 2021, NO HERBICIDE REP 4 | DOZEN | 3723 | $6.26 | | $23,305.98 |
| **VARIABLE COSTS** | | | | | |
| CRIMSON CLOVER | KG | 1.36 | $6.33 | $8.61 | $8.61 |
| CEREAL RYE | KG | 25.4 | $2.34 | $59.44 | $59.44 |
| RADISH | KG | 1.59 | $3.33 | $5.29 | $5.29 |
| SEED - PROVIDENCE | 1000 SEEDS | 49 | $18.63 | $912.87 | $912.87 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE | LITER | 1.18 | $6.37 | $7.52 | - |
| DUAL II MAGNUM | LITER | 0.71 | $17.00 | $12.07 | - |
| CROP OIL CONCENTRATE | LITER | 1.42 | $15.80 | $22.44 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $53.28 | $51.49 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $3,113.94 | $3,070.13 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| MOWING | HECTARE | 1 | $54.94 | $54.94 | $54.94 |
| DISKING | HECTARE | 1 | $25.39 | $25.39 | $25.39 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS | HECTARE | 1 | $25.94 | $25.94 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $10.59 | $9.49 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $718.75 | $691.71 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,832.69 | $3,761.84 |
| NET PROFIT REP 1 | | | | $16,099.15 | $15,606.60 |
| NET PROFIT REP 2 | | | | $16,380.85 | $13,083.82 |
| NET PROFIT REP 3 | | | | $14,415.21 | $19,544.14 |
| NET PROFIT REP 4 | | | | $18,346.49 | $19,544.14 |

Assumptions:

No other post harvest or marketing expenses included

**Table S7. Income, Variable Costs and Fixed Costs : NT 2021**

| SWEET CORN, NT - PER HECTARE 2021 | | | | Herbicide | No Herbicide |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN,NT 2021, HERBICIDE REP 1 | DOZEN | 2242 | $6.26 | $14,034.92 | |
| SWEET CORN,NT 2021, HERBICIDE REP 2 | DOZEN | 3095 | $6.26 | $19,374.70 | |
| SWEET CORN,NT 2021, HERBICIDE REP 3 | DOZEN | 3409 | $6.26 | $21,340.34 | |
| SWEET CORN,NT 2021, HERBICIDE REP 4 | DOZEN | 2646 | $6.26 | $16,563.96 | |
| SWEET CORN, NT 2021, NO HERBICIDE REP 1 | DOZEN | 1256 | $6.26 | | $7,862.56 |
| SWEET CORN, NT 2021, NO HERBICIDE REP 2 | DOZEN | 1435 | $6.26 | | $8,983.10 |
| SWEET CORN, NT 2021, NO HERBICIDE REP 3 | DOZEN | 2736 | $6.26 | | $17,127.36 |
| SWEET CORN, NT 2021, NO HERBICIDE REP 4 | DOZEN | 1704 | $6.26 | | $10,667.04 |
| **VARIABLE COSTS** | | | | | |
| CRIMSON CLOVER | KG | 1.36 | $6.33 | $8.61 | $8.61 |
| CEREAL RYE | KG | 25.4 | $2.34 | $59.44 | $59.44 |
| RADISH | KG | 1.59 | $3.33 | $5.29 | $5.29 |
| SEED - PROVIDENCE | 1000 SEEDS | 49 | $18.63 | $912.87 | $912.87 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE | LITER | 1.18 | $6.37 | $7.52 | - |
| DUAL II MAGNUM | LITER | 0.71 | $17.00 | $12.07 | - |
| CROP OIL CONCENTRATE | LITER | 1.42 | $15.80 | $22.44 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $53.28 | $51.49 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $3,113.94 | $3,070.13 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| ROLLER CRIMPER | HECTARE | 1 | $40.77 | $40.77 | $40.77 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS | HECTARE | 1 | $25.94 | $25.94 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $8.91 | $7.81 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $677.51 | $650.47 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,791.45 | $3,720.59 |
| NET PROFIT REP 1 | | | | $10,243.47 | $4,141.97 |
| NET PROFIT REP 2 | | | | $15,583.25 | $5,262.51 |
| NET PROFIT REP 3 | | | | $17,548.89 | $13,406.77 |
| NET PROFIT REP 4 | | | | $12,772.51 | $6,946.45 |

Assumptions:

No other post harvest or marketing expenses included

**Table S8. Income, Variable Costs and Fixed Costs : LMFR 2021**

| SWEET CORN, LMFR - PER HECTARE 2021 | | | | Herbicide | No Herbicide |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN, LMFR 2021, HERBICIDE REP 1 | DOZEN | 1973 | $6.26 | $12,350.98 | |
| SWEET CORN, LMFR 2021, HERBICIDE REP 2 | DOZEN | 2915 | $6.26 | $18,247.90 | |
| SWEET CORN, LMFR 2021, HERBICIDE REP 3 | DOZEN | 3454 | $6.26 | $21,622.04 | |
| SWEET CORN, LMFR 2021, HERBICIDE REP 4 | DOZEN | 3050 | $6.26 | $19,093.00 | |
| SWEET CORN, LMFR 2021, NO HERBICIDE REP 1 | DOZEN | 538 | $6.26 | | $3,367.88 |
| SWEET CORN, LMFR 2021, NO HERBICIDE REP 2 | DOZEN | 1749 | $6.26 | | $10,948.74 |
| SWEET CORN, LMFR 2021, NO HERBICIDE REP 3 | DOZEN | 1345 | $6.26 | | $8,419.70 |
| SWEET CORN, LMFR 2021, NO HERBICIDE REP 4 | DOZEN | 2377 | $6.26 | | $14,880.02 |
| **VARIABLE COSTS** | | | | | |
| RED CLOVER | KG | 6.8 | $9.33 | $63.44 | $63.44 |
| RADISH | KG | 4.54 | $3.33 | $15.12 | $15.12 |
| SEED - PROVIDENCE | 1000 SEEDS | 20 | $18.63 | $372.60 | $372.60 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE (.5ac) | QUART | 0.625 | $6.37 | $3.98 | - |
| DUAL II MAGNUM (.5ac) | QUART | 0.375 | $17.00 | $6.38 | - |
| CROP OIL CONCENTRATE (.5ac) | QUART | 0.75 | $15.80 | $11.85 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $29.69 | $28.75 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $2,535.49 | $2,512.34 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| ROLLER CRIMPER | HECTARE | 1 | $40.77 | $40.77 | $40.77 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS (.5ac) | HECTARE | 1 | $12.97 | $12.97 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $8.36 | $7.81 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $663.99 | $650.47 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,199.48 | $3,162.81 |
| NET PROFIT REP 1 | | | | $9,151.50 | $205.07 |
| NET PROFIT REP 2 | | | | $15,048.42 | $7,785.93 |
| NET PROFIT REP 3 | | | | $18,416.30 | $5,256.89 |
| NET PROFIT REP 4 | | | | $15,893.52 | $11,717.21 |

Assumptions:
No other post harvest or marketing expenses included
.5ac is the application on a half acre of the plot (herbicide banded)

**Table S9. Income, Variable Costs and Fixed Costs : LMRye 2021**

| **SWEET CORN, LMRye - PER HECTARE 2021** | | | | **Herbicide** | **No Herbicide** |
|---|---|---|---|---|---|
| ITEM | UNIT | QUANTITY | PRICE | TOTAL | TOTAL |
| **INCOME** | | | | | |
| SWEET CORN, LMRye 2021, HERBICIDE REP 1 | DOZEN | 1301 | $6.26 | $8,144.26 | |
| SWEET CORN, LMRye 2021, HERBICIDE REP 2 | DOZEN | 2736 | $6.26 | $17,127.36 | |
| SWEET CORN, LMRye 2021, HERBICIDE REP 3 | DOZEN | 2242 | $6.26 | $14,034.92 | |
| SWEET CORN, LMRye 2021, HERBICIDE REP 4 | DOZEN | 2063 | $6.26 | $12,914.38 | |
| SWEET CORN, LMRye 2021, NO HERBICIDE REP 1 | DOZEN | 359 | $6.26 | | $2,247.34 |
| SWEET CORN, LMRye 2021, NO HERBICIDE REP 2 | DOZEN | 852 | $6.26 | | $5,333.52 |
| SWEET CORN, LMRye 2021, NO HERBICIDE REP 3 | DOZEN | 1211 | $6.26 | | $7,580.86 |
| SWEET CORN, LMRye 2021, NO HERBICIDE REP 4 | DOZEN | 493 | $6.26 | | $3,086.18 |
| **VARIABLE COSTS** | | | | | |
| RED CLOVER | KG | 3.63 | $9.33 | $33.87 | $33.87 |
| CEREAL RYE | KG | 30.39 | $2.34 | $71.11 | $71.11 |
| SEED - PROVIDENCE | 1000 SEEDS | 20 | $18.63 | $372.60 | $372.60 |
| SOIL TEST | HECTARE | 1 | $3.06 | $3.06 | $3.06 |
| NITROGEN | KG | 63.5 | $1.53 | $97.16 | $97.16 |
| SULFUR | KG | 11.34 | $2.00 | $22.68 | $22.68 |
| ATRAZINE (.5ac) | QUART | 0.625 | $6.37 | $3.98 | - |
| DUAL II MAGNUM (.5ac) | QUART | 0.375 | $17.00 | $6.38 | - |
| CROP OIL CONCENTRATE (.5ac) | QUART | 0.75 | $15.80 | $11.85 | - |
| IRRIGATION EXPENSE (eletric, fuel, etc) | CM | 25.4 | $3.06 | $77.72 | $77.72 |
| IRRIGATION REPAIR & MAINTENANCE | HECTARE | 1 | $24.71 | $24.71 | $24.71 |
| LABOR - HARVEST | HOUR | 61.8 | $17.00 | $1,050.60 | $1,050.60 |
| LABOR - GRADING | HOUR | 44.5 | $17.00 | $756.50 | $756.50 |
| INTEREST ON OPERATING CAPITAL | UNIT | 0.5 | 8.5% | $30.82 | $29.87 |
| TOTAL VARIABLE COSTS LISTED ABOVE | | | | $2,563.03 | $2,539.88 |
| **FIXED COSTS** | | | | | |
| BROADCAST SEEDING SMGRAIN | HECTARE | 2 | $27.68 | $55.36 | $55.36 |
| ROLLER CRIMPER | HECTARE | 1 | $40.77 | $40.77 | $40.77 |
| NO-TILL PLANTING WITH FERTILIZER | HECTARE | 1 | $58.84 | $58.84 | $58.84 |
| FERTILIZER APPLICATION | HECTARE | 1 | $28.69 | $28.69 | $28.69 |
| PESTICIDE APPLICATIONS (.5ac) | HECTARE | 1 | $12.97 | $12.97 | - |
| INTEREST ON SPRING CUSTOM CHARGES | UNIT | 0.5 | 8.5% | $8.36 | $7.81 |
| IRRIGATION PAYMENT (including interest) | HECTARE | 1 | $150.00 | $150.00 | $150.00 |
| LAND CHARGE | HECTARE | 1 | $309.00 | $309.00 | $309.00 |
| TOTAL FIXED COST LISTED ABOVE | | | | $663.99 | $650.47 |
| TOTAL VARIABLE AND FIXED COST | | | | $3,227.02 | $3,190.35 |
| NET PROFIT REP 1 | | | | $4,917.24 | ($943.01) |
| NET PROFIT REP 2 | | | | $13,900.34 | $2,143.17 |
| NET PROFIT REP 3 | | | | $10,807.90 | $4,390.51 |
| NET PROFIT REP 4 | | | | $9,687.36 | ($104.17) |

Assumptions:

No other post harvest or marketing expenses included

.5ac is the application on a half acre of the plot (herbicide banded)

**Table S10. Taxon Totals - Visual Observations 2019**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| | 2019 | | | |
| Anthocoridae | 423 | 537 | 261 | 260 |
| Aranea | 31 | 24 | 42 | 55 |
| Cantharidae | 15 | 20 | 17 | 23 |
| Chrysomelidae | 161 | 161 | 97 | 117 |
| Chrysopidae | 10 | 8 | 7 | 4 |
| Cicadellidae | 80 | 140 | 84 | 89 |
| Coccinellidae | 115 | 107 | 58 | 34 |
| Curculionidae | 11 | 2 | 5 | 7 |
| Dolichopodidae | 29 | 32 | 42 | 43 |
| Elateridae | 13 | 3 | 3 | 1 |
| Geocoridae | 6 | 7 | 23 | 15 |
| Lampyridae | 8 | 8 | 17 | 4 |
| Lygaeidae | 6 | 4 | 0 | 0 |
| Miridae | 74 | 55 | 42 | 83 |
| Nabidae | 16 | 12 | 0 | 2 |
| Nitidulidae | 6 | 9 | 1 | 5 |
| Pentatomidae (pred) | 3 | 2 | 11 | 16 |
| Pentatomidae (pest) | 2 | 0 | 0 | 1 |
| Reduviidae | 0 | 0 | 1 | 2 |
| Staphylinidae | 3 | 0 | 4 | 1 |
| Syrphidae | 13 | 9 | 8 | 14 |

**Table S11. Taxon Totals - Visual Observations 2020**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Anthocoridae | 284 | 278 | 264 | 194 |
| Aranea | 82 | 55 | 57 | 50 |
| Cantharidae | 2 | 4 | 2 | 5 |
| Chrysomelidae | 103 | 79 | 77 | 53 |
| Chrysopidae | 31 | 28 | 18 | 22 |
| Cicadellidae | 183 | 157 | 314 | 216 |
| Coccinellidae | 90 | 110 | 69 | 41 |
| Curculionidae | 4 | 3 | 5 | 2 |
| Elateridae | 1 | 3 | 0 | 4 |
| Geocoridae | 1 | 1 | 5 | 4 |
| Lampyridae | 2 | 9 | 8 | 6 |
| Miridae | 34 | 36 | 51 | 50 |
| Nabidae | 1 | 0 | 2 | 2 |
| Nitidulidae | 16 | 12 | 8 | 4 |
| Pentatomidae (pred) | 10 | 10 | 17 | 10 |
| Pentatomidae (pest) | 0 | 2 | 2 | 0 |
| Reduviidae | 0 | 0 | 0 | 2 |
| Staphylinidae | 1 | 0 | 0 | 0 |
| Syrphidae | 2 | 0 | 0 | 1 |

**Table S12. Taxon Totals - Visual Observations 2021**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Anthocoridae | 592 | 557 | 457 | 365 |
| Aranea | 31 | 32 | 39 | 42 |
| Cantharidae | 0 | 3 | 4 | 2 |
| Chrysomelidae | 89 | 45 | 7 | 37 |
| Chrysopidae | 2 | 1 | 0 | 1 |
| Cicadellidae | 89 | 113 | 112 | 92 |
| Coccinellidae | 26 | 30 | 23 | 19 |
| Curculionidae | 7 | 4 | 7 | 3 |
| Elateridae | 13 | 6 | 7 | 5 |
| Geocoridae | 1 | 1 | 3 | 9 |
| Lampyridae | 1 | 1 | 2 | 5 |
| Miridae | 121 | 86 | 85 | 83 |
| Nabidae | 2 | 6 | 0 | 1 |
| Nitidulidae | 1 | 0 | 1 | 0 |
| Pentatomidae (pred) | 2 | 11 | 5 | 10 |
| Pentatomidae (pest) | 0 | 0 | 0 | 1 |
| Reduviidae | 0 | 0 | 0 | 1 |
| Staphylinidae | 0 | 0 | 0 | 0 |
| Syrphidae | 1 | 4 | 2 | 5 |

**Table S13. Taxon Totals – Sticky Cards 2019**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 0 | 0 | 2 | 1 |
| Aeolothripidae | 1 | 1 | 3 | 0 |
| Agromyzidae | 0 | 2 | 0 | 0 |
| Aleyrodidae | 2 | 12 | 46 | 27 |
| Anthicidae | 1 | 1 | 0 | 0 |
| Anthocoridae | 829 | 822 | 526 | 484 |
| Aphelinidae | 10 | 34 | 31 | 34 |
| Aphididae | 13 | 27 | 12 | 31 |
| Araneae | 1 | 0 | 0 | 0 |
| Bethylidae | 3 | 1 | 0 | 0 |
| Blissidae | 0 | 2 | 0 | 1 |
| Braconidae | 3 | 9 | 32 | 26 |
| Carabidae | 2 | 9 | 4 | 2 |
| Ceraphronidae | 350 | 144 | 130 | 55 |
| Cercopidae | 0 | 1 | 0 | 0 |
| Chalcididae | 1 | 0 | 0 | 0 |
| Chrysomelidae | 208 | 178 | 102 | 138 |
| Cicadellidae | 509 | 693 | 793 | 1081 |
| Coccinellidae | 88 | 81 | 60 | 42 |
| Curculionidae | 0 | 2 | 4 | 9 |
| Cydnidae | 4 | 8 | 33 | 20 |
| Delphacidae | 4 | 0 | 3 | 1 |
| Derbidae | 3 | 2 | 6 | 10 |
| Diapriidae | 4 | 6 | 4 | 6 |
| Dolichopodidae | 63 | 52 | 52 | 46 |
| Elateridae | 2 | 2 | 0 | 0 |
| Encyrtidae | 11 | 8 | 38 | 37 |
| Eulophidae | 19 | 22 | 22 | 22 |
| Eupelmidae | 1 | 0 | 0 | 0 |
| Eurytomidae | 1 | 4 | 79 | 166 |
| Figitidae | 85 | 112 | 238 | 256 |
| Formicidae | 1 | 2 | 14 | 3 |
| Geocoridae | 18 | 12 | 89 | 101 |
| Halictidae | 0 | 0 | 1 | 0 |
| Hybotidae | 1 | 5 | 8 | 44 |
| Ichneumonidae | 0 | 2 | 2 | 3 |
| Lampyridae | 11 | 7 | 7 | 15 |
| Linyphiidae | 0 | 0 | 1 | 1 |
| Lygaeidae | 0 | 0 | 1 | 0 |
| Membracidae | 0 | 1 | 7 | 11 |
| Miridae | 51 | 44 | 79 | 77 |
| Monotomidae | 0 | 0 | 1 | 0 |
| Mymaridae | 142 | 143 | 127 | 132 |
| Mymarommatidae | 0 | 0 | 0 | 1 |
| Nabidae | 2 | 0 | 4 | 1 |
| Mitidulidae | 0 | 0 | 0 | 1 |
| Pentatomidae | 0 | 1 | 1 | 1 |

| | | | | |
|---|---|---|---|---|
| Platygastridae | 49 | 40 | 53 | 94 |
| Pompilidae | 1 | 0 | 0 | 0 |
| Platystomatidae | 0 | 1 | 1 | 0 |
| Psyllidae | 0 | 0 | 1 | 0 |
| Pteromalidae | 63 | 38 | 81 | 61 |
| Salticidae | 0 | 1 | 1 | 0 |
| Sarcophagidae | 16 | 41 | 20 | 21 |
| Scarabaeidae | 0 | 0 | 0 | 1 |
| Scelionidae | 159 | 159 | 217 | 221 |
| Sepsidae | 0 | 0 | 0 | 1 |
| Staphylinidae | 6 | 10 | 11 | 7 |
| Syrphidae | 1 | 2 | 1 | 2 |
| Tachinidae | 0 | 1 | 0 | 1 |
| Tettigoniidae | 5 | 5 | 8 | 1 |
| Therevidae | 0 | 0 | 1 | 0 |
| Thomisidae | 0 | 0 | 0 | 1 |
| Thripidae | 95 | 133 | 609 | 755 |
| Trichogrammatidae | 133 | 86 | 229 | 242 |
| Ulidiidae | 109 | 103 | 96 | 54 |

**Table S14. Taxon Totals – Sticky Cards 2020**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 0 | 2 | 1 | 1 |
| Aeolothripidae | 8 | 6 | 18 | 18 |
| Agromyzidae | 0 | 1 | 1 | 0 |
| Aleyrodidae | 13 | 20 | 21 | 20 |
| Alydidae | 0 | 2 | 2 | 1 |
| Anthicidae | 0 | 1 | 0 | 0 |
| Anthocoridae | 351 | 243 | 385 | 389 |
| Aphelinidae | 144 | 163 | 114 | 71 |
| Aphididae | 103 | 138 | 53 | 142 |
| Araneae | 0 | 1 | 3 | 0 |
| Bethylidae | 0 | 6 | 2 | 1 |
| Blissidae | 0 | 0 | 0 | 0 |
| Braconidae | 10 | 7 | 8 | 31 |
| Cantharidae | 1 | 0 | 3 | 5 |
| Carabidae | 4 | 0 | 3 | 3 |
| Ceraphronidae | 257 | 63 | 92 | 56 |
| Ceratocombidae | 0 | 1 | 0 | 0 |
| Cercopidae | 1 | 1 | 0 | 0 |
| Chalcididae | 1 | 0 | 5 | 0 |
| Chrysididae | 0 | 0 | 0 | 1 |
| Chrysomelidae | 90 | 55 | 55 | 55 |
| Chrysopidae | 1 | 0 | 0 | 0 |
| Cicadellidae | 1018 | 1080 | 1572 | 1331 |
| Clastopteridae | 0 | 1 | 0 | 3 |
| Coccinellidae | 157 | 167 | 104 | 59 |
| Crabronidae | 0 | 0 | 1 | 1 |
| Curculionidae | 1 | 0 | 1 | 0 |
| Cydnidae | 7 | 8 | 20 | 25 |
| Delphacidae | 2 | 6 | 4 | 0 |
| Derbidae | 23 | 8 | 10 | 11 |
| Diapriidae | 6 | 8 | 3 | 3 |
| Dolichopodidae | 7 | 5 | 2 | 5 |
| Elateridae | 0 | 2 | 1 | 1 |
| Encyrtidae | 4 | 6 | 8 | 14 |
| Eulophidae | 11 | 15 | 12 | 18 |
| Eupelmidae | 0 | 0 | 0 | 1 |
| Eurytomidae | 0 | 1 | 15 | 27 |
| Figitidae | 23 | 25 | 41 | 38 |
| Formicidae | 31 | 10 | 11 | 7 |
| Geocoridae | 4 | 6 | 39 | 57 |
| Gryllidae | 1 | 0 | 1 | 0 |
| Hybotidae | 1 | 0 | 0 | 1 |
| Ichneumonidae | 0 | 2 | 0 | 0 |
| Lampyridae | 11 | 0 | 0 | 0 |
| Libellulidae | 1 | 0 | 0 | 0 |
| Linyphiidae | 4 | 9 | 1 | 0 |
| Lygaeidae | 0 | 0 | 1 | 0 |

| | | | | |
|---|---|---|---|---|
| Megaspilidae | 1 | 0 | 0 | 0 |
| Melyridae | 1 | 3 | 1 | 0 |
| Membracidae | 1 | 0 | 6 | 11 |
| Miridae | 38 | 43 | 34 | 98 |
| Monotomidae | 1 | 0 | 0 | 0 |
| Mymaridae | 281 | 296 | 328 | 232 |
| Mymarommatidae | 1 | 0 | 2 | 2 |
| Nabidae | 0 | 1 | 1 | 1 |
| Mitidulidae | 0 | 0 | 0 | 1 |
| Pentatomidae | 0 | 1 | 0 | 1 |
| Platygastridae | 10 | 28 | 18 | 33 |
| Psyllidae | 0 | 1 | 0 | 0 |
| Pteromalidae | 7 | 11 | 13 | 14 |
| Rhyparochromidae | 0 | 1 | 0 | 0 |
| Salticidae | 0 | 0 | 1 | 0 |
| Sarcophagidae | 14 | 14 | 12 | 9 |
| Scarabaeidae | 0 | 0 | 0 | 0 |
| Scelionidae | 181 | 281 | 327 | 218 |
| Sepsidae | 0 | 0 | 0 | 0 |
| Silvanidae | 1 | 1 | 0 | 0 |
| Staphylinidae | 3 | 1 | 1 | 5 |
| Syrphidae | 1 | 0 | 0 | 0 |
| Tenthredinidae | 1 | 0 | 0 | 0 |
| Tettigoniidae | 1 | 1 | 2 | 1 |
| Therevidae | 0 | 0 | 1 | 0 |
| Thripidae | 328 | 467 | 600 | 697 |
| Thyreocoridae | 0 | 1 | 1 | 1 |
| Torymidae | 0 | 0 | 1 | 0 |
| Trichogrammatidae | 88 | 80 | 201 | 160 |
| Ulidiidae | 36 | 34 | 38 | 34 |

**Table S15. Taxon Totals – Sticky Cards 2021**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 4 | 6 | 9 | 13 |
| Aeolothripidae | 5 | 10 | 12 | 13 |
| Aleyrodidae | 28 | 39 | 152 | 144 |
| Anthicidae | 0 | 1 | 2 | 0 |
| Anthocoridae | 530 | 400 | 474 | 456 |
| Aphelinidae | 148 | 65 | 58 | 55 |
| Aphididae | 137 | 120 | 89 | 83 |
| Araneae | 0 | 2 | 2 | 0 |
| Asilidae | 0 | 0 | 0 | 1 |
| Berytidae | 1 | 0 | 0 | 0 |
| Bethylidae | 0 | 3 | 1 | 2 |
| Braconidae | 8 | 7 | 10 | 11 |
| Cantharidae | 0 | 0 | 0 | 2 |
| Carabidae | 1 | 1 | 2 | 1 |
| Ceraphronidae | 120 | 74 | 57 | 63 |
| Cercopidae | 2 | 1 | 1 | 2 |
| Chalcididae | 1 | 1 | 1 | |
| Chrysomelidae | 159 | 21 | 23 | 23 |
| Chrysopidae | 0 | 0 | 0 | 2 |
| Cicadellidae | 955 | 982 | 1786 | 1281 |
| Clastopteridae | 11 | 8 | 2 | 6 |
| Coccinellidae | 146 | 113 | 126 | 73 |
| Crabronidae | 3 | 3 | 0 | 0 |
| Curculionidae | 2 | 3 | 4 | 12 |
| Cydnidae | 1 | 3 | 5 | 4 |
| Delphacidae | 3 | 0 | 1 | 1 |
| Derbidae | 0 | 4 | 2 | 0 |
| Diapriidae | 1 | 4 | 1 | 2 |
| Dolichopodidae | 58 | 35 | 29 | 46 |
| Elateridae | 5 | 0 | 5 | 7 |
| Encyrtidae | 20 | 38 | 36 | 54 |
| Erotylidae | 0 | 0 | 2 | 0 |
| Eulophidae | 34 | 17 | 24 | 15 |
| Eupelmidae | 0 | 2 | 0 | 1 |
| Eurytomidae | 0 | 0 | 13 | 10 |
| Figitidae | 88 | 96 | 87 | 90 |
| Formicidae | 47 | 6 | 15 | 30 |
| Geocoridae | 16 | 4 | 55 | 56 |
| Gryllidae | 0 | 1 | 0 | 0 |
| Hybotidae | 0 | 0 | 1 | 4 |
| Hydrophilidae | 0 | 1 | 0 | 0 |
| Ichneumonidae | 0 | 1 | 0 | 0 |
| Lampyridae | 0 | 1 | 1 | 0 |
| Libellulidae | 0 | 1 | 0 | 0 |
| Linyphiidae | 3 | 0 | 0 | 1 |
| Lygaeidae | 8 | 3 | 12 | 2 |
| Megaspilidae | 0 | 1 | 2 | 1 |

| | | | | |
|---|---|---|---|---|
| Melyridae | 1 | 3 | 1 | 2 |
| Membracidae | 2 | 3 | 5 | 5 |
| Miridae | 109 | 73 | 105 | 119 |
| Mordellidae | 0 | 0 | 0 | 3 |
| Mymaridae | 119 | 148 | 192 | 145 |
| Mymarommatidae | 0 | 1 | 2 | 0 |
| Nitidulidae | 0 | 0 | 1 | 0 |
| Pentatomidae | 0 | 0 | 2 | 0 |
| Platygastridae | 25 | 15 | 7 | 13 |
| Platystomatidae | 1 | 0 | 0 | 1 |
| Psyllidae | 1 | 1 | 3 | 0 |
| Pteromalidae | 18 | 16 | 17 | 10 |
| Rhyparochromidae | 3 | 1 | 2 | 1 |
| Saldidae | 0 | 2 | 1 | 1 |
| Salticidae | 0 | 1 | 0 | 0 |
| Sarcophagidae | 16 | 22 | 35 | 18 |
| Scelionidae | 190 | 237 | 208 | 279 |
| Signiphoridae | 0 | 0 | 0 | 1 |
| Sierolomorphidae | 1 | 0 | 0 | 0 |
| Silvanidae | 1 | 1 | 1 | 0 |
| Staphylinidae | 3 | 3 | 2 | 3 |
| Stratiomyidae | 1 | 0 | 0 | 0 |
| Syrphidae | 7 | 0 | 4 | 5 |
| Tetragnathidae | 0 | 1 | 0 | 0 |
| Tettigoniidae | 0 | 1 | 4 | 10 |
| Thomisidae | 1 | 0 | 1 | 0 |
| Thripidae | 432 | 628 | 1660 | 1759 |
| Thyreocoridae | 0 | 0 | 0 | 0 |
| Torymidae | 0 | 0 | 0 | 0 |
| Trichogrammatidae | 110 | 164 | 310 | 369 |
| Ulidiidae | 51 | 63 | 40 | 87 |

**Table S16. Taxon Totals – Emergence Cages 2020**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 0 | 2 | 3 | 1 |
| Aleothripidae | 0 | 0 | 1 | 0 |
| Agromyziadae | 10 | 5 | 4 | 1 |
| Aleyrodidae | 3 | 7 | 6 | 8 |
| Alydidae | 0 | 0 | 4 | 0 |
| Anthicidae | 26 | 5 | 1 | 3 |
| Anthocoridae | 1 | 3 | 8 | 9 |
| Anthomyiidae | 0 | 0 | 0 | 1 |
| Anthomyzidae | 4 | 3 | 7 | 9 |
| Aphididae | 18 | 28 | 8 | 2 |
| Araneae | 1 | 1 | 4 | 0 |
| Asteiidae | 1 | 2 | 1 | 1 |
| Berytidae | 0 | 1 | 0 | 0 |
| Bethylidae | 1 | 6 | 3 | 2 |
| Braconidae | 8 | 22 | 25 | 15 |
| Cantharidae | 1 | 2 | 26 | 11 |
| Carabidae | 5 | 20 | 13 | 6 |
| Cecidomyiidae | 835 | 1192 | 3016 | 1133 |
| Ceraphronidae | 34 | 31 | 61 | 39 |
| Ceratocombidae | 1 | 3 | 6 | 0 |
| Ceratopogonidae | 353 | 326 | 166 | 138 |
| Chironomidae | 4 | 22 | 54 | 94 |
| Chloropidae | 230 | 283 | 352 | 308 |
| Chrysomelidae | 5 | 8 | 4 | 5 |
| Chrysopidae | 1 | 0 | 0 | 0 |
| Cicadellidae | 35 | 43 | 95 | 75 |
| Clubonidae | 1 | 0 | 2 | 0 |
| Coccinellidae | 16 | 27 | 13 | 13 |
| Corylophidae | 0 | 3 | 3 | 1 |
| Crabronidae | 0 | 0 | 0 | 0 |
| Curculionidae | 0 | 1 | 14 | 6 |
| Cydnidae | 2 | 4 | 14 | 17 |
| Delphacidae | 18 | 7 | 6 | 2 |
| Derbidae | 0 | 0 | 0 | 1 |
| Diapriidae | 14 | 4 | 9 | 26 |
| Dolichopodidae | 82 | 56 | 52 | 29 |
| Dropsophilidae | 0 | 4 | 4 | 2 |
| Dyrinidae | 1 | 1 | 0 | 0 |
| Elateridae | 13 | 11 | 24 | 8 |
| Encyrtidae | 0 | 1 | 7 | 2 |
| Enicocephalidae | 1 | 0 | 2 | 1 |
| Ephydridae | 35 | 17 | 13 | 8 |
| Erotylidae | 13 | 15 | 11 | 6 |
| Eulophidae | 3 | 1 | 3 | 5 |
| Eupelmidae | 0 | 0 | 0 | 1 |
| Eurytomidae | 0 | 0 | 19 | 26 |
| Figitidae | 9 | 17 | 23 | 28 |

| | | | | |
|---|---|---|---|---|
| Formicidae | 169 | 142 | 108 | 459 |
| Geocoridae | 0 | 1 | 7 | 1 |
| Gnaphosidae | 0 | 0 | 1 | 0 |
| Gryllidae | 0 | 1 | 1 | 8 |
| Halictidae | 0 | 1 | 0 | 1 |
| Henicopidae | 1 | 6 | 4 | 2 |
| Heteroceridae | 2 | 3 | 0 | 0 |
| Hybotidae | 1 | 7 | 14 | 9 |
| Hydrophilidae | 21 | 46 | 29 | 4 |
| Ichneumonidae | 3 | 1 | 3 | 0 |
| Lampyridae | 0 | 1 | 1 | 0 |
| Latridiidae | 36 | 21 | 24 | 13 |
| Lauxaniidae | 0 | 0 | 0 | 1 |
| Limoniidae | 2 | 8 | 25 | 40 |
| Linyphiidae | 7 | 18 | 23 | 12 |
| Lycosidae | 0 | 0 | 2 | 1 |
| Megaspilidae | 0 | 2 | 1 | 1 |
| Melyridae | 1 | 2 | 0 | 1 |
| Miridae | 2 | 6 | 7 | 6 |
| Monotomidae | 0 | 0 | 0 | 1 |
| Mordellidae | 0 | 0 | 1 | 0 |
| Muscidae | 4 | 1 | 6 | 2 |
| Mutillidae | 1 | 2 | 2 | 1 |
| Mycetophagidae | 1 | 2 | 1 | 0 |
| Mycetophilidae | 0 | 1 | 4 | 0 |
| Mymaridae | 60 | 103 | 267 | 171 |
| Nabidae | 1 | 0 | 0 | 0 |
| Nitidulidae | 9 | 49 | 19 | 28 |
| Oxyopidae | 2 | 0 | 1 | 0 |
| Pentatomidae | 0 | 7 | 2 | 0 |
| Phalacridae | 6 | 15 | 16 | 7 |
| Phoridae | 25 | 58 | 57 | 55 |
| Pipunculidae | 0 | 0 | 3 | 0 |
| Plastaspidae | 0 | 0 | 0 | 1 |
| Platygastridae | 42 | 38 | 52 | 60 |
| Polleniidae | 0 | 1 | 0 | 0 |
| Pompilidae | 3 | 6 | 4 | 2 |
| Psyllidae | 0 | 0 | 26 | 7 |
| Pteromalidae | 1 | 9 | 21 | 7 |
| Ptiliidae | 1 | 1 | 0 | 4 |
| Rhyparochromidae | 9 | 6 | 13 | 12 |
| Saldidae | 1 | 1 | 0 | 0 |
| Salticidae | 0 | 2 | 5 | 2 |
| Sarcophagidae | 1 | 2 | 5 | 1 |
| Scarabdaeidae | 2 | 0 | 1 | 1 |
| Scatopsidae | 2 | 21 | 27 | 141 |
| Scelionidae | 76 | 247 | 173 | 135 |
| Sciaridae | 18 | 37 | 44 | 42 |
| Scoliidae | 0 | 0 | 1 | 0 |
| Sierolomorphidae | 0 | 0 | 0 | 2 |
| Silvanidae | 6 | 10 | 10 | 1 |

| | | | | |
|---|---|---|---|---|
| Sphaeroceridae | 1 | 3 | 12 | 11 |
| Staphylinidae | 93 | 305 | 250 | 327 |
| Stenomicridae | 0 | 1 | 0 | 0 |
| Syrphidae | 1 | 0 | 1 | 1 |
| Tachinidae | 0 | 1 | 1 | 1 |
| Tenebrionidae | 1 | 0 | 0 | 0 |
| Tetragnathidae | 1 | 0 | 1 | 0 |
| Tettigoniidae | 0 | 0 | 1 | 0 |
| Thomisidae | 0 | 7 | 4 | 3 |
| Thyreocoridae | 0 | 0 | 1 | 0 |
| Tiphiidae | 0 | 1 | 0 | 2 |
| Trichogrammatidae | 3 | 6 | 29 | 17 |
| Ulidiidae | 3 | 2 | 3 | 0 |

**Table S17. Taxon Totals – Emergence Cages 2021**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 0 | 0 | 0 | 0 |
| Aleothripidae | 0 | 0 | 0 | 0 |
| Agromyziadae | 0 | 1 | 1 | 1 |
| Aleyrodidae | 4 | 47 | 18 | 25 |
| Alydidae | 0 | 1 | 1 | 6 |
| Anthicidae | 50 | 11 | 11 | 1 |
| Anthocoridae | 0 | 14 | 5 | 33 |
| Anthomyiidae | 0 | 0 | 0 | 1 |
| Anthomyzidae | 0 | 29 | 12 | 28 |
| Aphelinidae | 1 | 0 | 0 | 3 |
| Aphididae | 87 | 69 | 50 | 10 |
| Araneae | 0 | 0 | 2 | 0 |
| Asilidae | 0 | 0 | 1 | 0 |
| Bethylidae | 0 | 5 | 1 | 0 |
| Blissidae | 1 | 0 | 0 | 0 |
| Braconidae | 8 | 21 | 9 | 26 |
| Cantharidae | 0 | 3 | 31 | 24 |
| Carabidae | 7 | 19 | 6 | 23 |
| Cecidomyiidae | 163 | 927 | 431 | 989 |
| Ceraphronidae | 41 | 93 | 30 | 57 |
| Ceratocombidae | 0 | 5 | 1 | 2 |
| Ceratopogonidae | 11 | 30 | 7 | 21 |
| Chironomidae | 3 | 32 | 0 | 62 |
| Chloropidae | 28 | 245 | 176 | 430 |
| Chrysomelidae | 3 | 4 | 3 | 7 |
| Chrysopidae | 0 | 0 | 0 | 0 |
| Cicadellidae | 51 | 141 | 90 | 50 |
| Clubonidae | 0 | 0 | 0 | 0 |
| Coccinellidae | 5 | 7 | 6 | 5 |
| Corylophidae | 4 | 3 | 3 | 0 |
| Crabronidae | 0 | 0 | 0 | 3 |
| Culicidae | 1 | 0 | 0 | 0 |
| Curculionidae | 0 | 0 | 1 | 2 |
| Cydnidae | 1 | 2 | 5 | 0 |
| Delphacidae | 7 | 8 | 6 | 10 |
| Derbidae | 1 | 1 | 0 | 1 |
| Diapriidae | 5 | 28 | 7 | 17 |
| Dolichopodidae | 15 | 23 | 34 | 30 |
| Dropsophilidae | 0 | 101 | 11 | 53 |
| Dyrinidae | 0 | 1 | 0 | 1 |
| Elateridae | 5 | 11 | 12 | 4 |
| Encyrtidae | 2 | 8 | 17 | 31 |
| Ephydridae | 6 | 5 | 4 | 1 |
| Erotylidae | 38 | 5 | 21 | 7 |
| Eulophidae | 0 | 5 | 11 | 11 |
| Eurytomidae | 0 | 1 | 95 | 157 |
| Figitidae | 6 | 102 | 53 | 196 |

| | | | | |
|---|---|---|---|---|
| Formicidae | 70 | 84 | 67 | 45 |
| Geocoridae | 1 | 0 | 0 | 1 |
| Gnaphosidae | 1 | 0 | 0 | 0 |
| Gryllidae | 0 | 3 | 12 | 2 |
| Halictidae | 2 | 0 | 0 | 0 |
| Henicopidae | 0 | 1 | 0 | 0 |
| Heteroceridae | 3 | 0 | 1 | 0 |
| Histeridae | 1 | 1 | 1 | 2 |
| Hybotidae | 0 | 55 | 2 | 20 |
| Hydrophilidae | 21 | 6 | 4 | 3 |
| Ichneumonidae | 1 | 3 | 5 | 7 |
| Lampyridae | 2 | 0 | 0 | 0 |
| Latridiidae | 14 | 18 | 11 | 6 |
| Lauxaniidae | 0 | 0 | 1 | 0 |
| Leiodidae | 0 | 1 | 0 | 0 |
| Limoniidae | 5 | 67 | 5 | 344 |
| Linyphiidae | 44 | 42 | 40 | 30 |
| Lycosidae | 1 | 0 | 2 | 1 |
| Lygaeidae | 2 | 0 | 0 | 0 |
| Megaspilidae | 0 | 0 | 1 | 1 |
| Melyridae | 0 | 0 | 0 | 0 |
| Membracidae | 3 | 2 | 1 | 2 |
| Miridae | 39 | 116 | 22 | 33 |
| Monotomidae | 0 | 0 | 0 | 3 |
| Mordellidae | 0 | 0 | 0 | 0 |
| Muscidae | 0 | 0 | 0 | 2 |
| Mutillidae | 1 | 1 | 1 | 1 |
| Mycetophagidae | 0 | 3 | 3 | 0 |
| Mycetophilidae | 0 | 4 | 1 | 3 |
| Mymaridae | 130 | 249 | 164 | 508 |
| Mymarommatidae | 0 | 0 | 1 | 0 |
| Nabidae | 0 | 0 | 5 | 7 |
| Nitidulidae | 5 | 19 | 2 | 55 |
| Oxyopidae | 0 | 2 | 2 | 0 |
| Pentatomidae | 0 | 0 | 1 | 2 |
| Phalacridae | 2 | 11 | 7 | 9 |
| Phoridae | 11 | 95 | 17 | 94 |
| Pipunculidae | 0 | 0 | 1 | 0 |
| Plastaspidae | 0 | 0 | 0 | 0 |
| Platygastridae | 12 | 18 | 1 | 10 |
| Polleniidae | 0 | 1 | 0 | 0 |
| Pompilidae | 1 | 7 | 9 | 9 |
| Psyllidae | 0 | 4 | 2 | 3 |
| Pteromalidae | 3 | 15 | 10 | 15 |
| Ptiliidae | 1 | 2 | 1 | 31 |
| Rhinotermitidae | 0 | 0 | 0 | 1 |
| Rhyparochromidae | 14 | 24 | 18 | 22 |
| Saldidae | 1 | 0 | 0 | 0 |
| Salticidae | 0 | 0 | 0 | 2 |
| Sarcophagidae | 0 | 2 | 1 | 13 |
| Scarabdaeidae | 25 | 34 | 48 | 23 |

| | | | | |
|---|---|---|---|---|
| Scatopsidae | 6 | 183 | 63 | 273 |
| Scelionidae | 109 | 297 | 115 | 240 |
| Sciaridae | 3 | 61 | 13 | 37 |
| Sciomyzidae | 0 | 0 | 1 | 0 |
| Scoliidae | 0 | 0 | 4 | 2 |
| Sepsidae | 0 | 1 | 0 | 0 |
| Silvanidae | 4 | 5 | 1 | 4 |
| Sphaeroceridae | 7 | 42 | 25 | 158 |
| Staphylinidae | 110 | 200 | 296 | 703 |
| Stenomicridae | 1 | 0 | 0 | 2 |
| Syrphidae | 0 | 1 | 0 | 0 |
| Tachinidae | 0 | 7 | 0 | 39 |
| Tetragnathidae | 1 | 7 | 4 | 6 |
| Therevidae | 0 | 1 | 1 | 1 |
| Thomisidae | 1 | 9 | 4 | 7 |
| Tiphiidae | 0 | 2 | 0 | 0 |
| Tipulidae | 0 | 0 | 0 | 1 |
| Trichogrammatidae | 5 | 18 | 21 | 18 |
| Ulidiidae | 1 | 0 | 0 | 0 |

**Table S18. Taxon Totals – Pitfall Traps 2020**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 1 | 0 | 0 | 0 |
| Alydidae | 0 | 2 | 0 | 0 |
| Anthicidae | 0 | 1 | 0 | 0 |
| Aphididae | 0 | 1 | 0 | 0 |
| Armadillidiidae | 4 | 0 | 0 | 0 |
| Braconidae | 3 | 5 | 5 | 0 |
| Cantharidae | 1 | 0 | 0 | 0 |
| Carabidae | 40 | 30 | 22 | 0 |
| Cecidomyiidae | 1 | 1 | 1 | 0 |
| Ceraphronidae | 1 | 0 | 0 | 0 |
| Cicindelidae | 0 | 1 | 0 | 0 |
| Clubonidae | 0 | 3 | 0 | 0 |
| Coccinellidae | 0 | 1 | 1 | 0 |
| Corylophidae | 0 | 0 | 4 | 0 |
| Curculionidae | 1 | 0 | 3 | 0 |
| Cydnidae | 0 | 0 | 19 | 0 |
| Diapriidae | 3 | 0 | 1 | 1 |
| Drosophilidae | 0 | 2 | 3 | 6 |
| Dysderidae | 1 | 0 | 0 | 0 |
| Ectobiidae | 0 | 0 | 1 | 1 |
| Elateridae | 3 | 2 | 1 | 2 |
| Erotylidae | 17 | 27 | 18 | 16 |
| Eulophidae | 0 | 0 | 0 | 1 |
| Figitidae | 0 | 0 | 0 | 2 |
| Formicidae | 93 | 97 | 61 | 107 |
| Gryllidae | 74 | 189 | 163 | 189 |
| Henicopidae | 13 | 3 | 3 | 7 |
| Histeridae | 2 | 0 | 2 | 3 |
| Hydrophilidae | 0 | 1 | 2 | 0 |
| Ichneumonidae | 0 | 0 | 2 | 1 |
| Latridiidae | 8 | 3 | 4 | 3 |
| Limoniidae | 0 | 0 | 0 | 1 |
| Linyphiidae | 20 | 6 | 3 | 7 |
| Lycosidae | 62 | 50 | 21 | 21 |
| Miridae | 0 | 0 | 1 | 1 |
| Monotomidae | 1 | 8 | 1 | 13 |
| Mutillidae | 2 | 0 | 0 | 0 |
| Mycetophagidae | 3 | 1 | 9 | 5 |
| Mymaridae | 2 | 0 | 0 | 2 |
| Nitidulidae | 48 | 80 | 156 | 160 |
| Pentatomidae | 0 | 1 | 2 | 1 |
| Phalacridae | 0 | 0 | 0 | 1 |
| Phoridae | 24 | 30 | 18 | 29 |
| Reduviidae | 0 | 0 | 1 | 0 |
| Rhyparochromidae | 6 | 20 | 3 | 20 |
| Sarcophagidae | 2 | 2 | 0 | 0 |
| Scarabaeidae | 28 | 30 | 8 | 5 |

| | | | | |
|---|---|---|---|---|
| Scelionidae | 34 | 43 | 32 | 75 |
| Sciaridae | 1 | 0 | 1 | 2 |
| Silvanidae | 10 | 10 | 13 | 25 |
| Sphaeroceridae | 0 | 02 | 1 | 0 |
| Staphylinidae | 16 | 24 | 28 | 68 |
| Tetrigidae | 0 | 0 | 0 | 1 |
| Tettigoniidae | 1 | 0 | 0 | 0 |
| Theridiidae | 0 | 1 | 0 | 0 |
| Thomisidae | 0 | 1 | 0 | 0 |
| Thyreocoridae | 0 | 0 | 1 | 1 |

**Table S19. Taxon Totals – Pitfall Traps 2021**

| Taxon | Treatment | | | |
|---|---|---|---|---|
| | CT | NT | LMFR | LMRye |
| Acrididae | 6 | 6 | 8 | 7 |
| Alydidae | 0 | 4 | 3 | 1 |
| Anthicidae | 2 | 2 | 2 | 1 |
| Anthocoridae | 2 | 1 | 0 | 2 |
| Anthomyiidae | 2 | 0 | 0 | 0 |
| Anthomyzidae | 0 | 0 | 2 | 3 |
| Aphididae | 0 | 1 | 1 | 2 |
| Araneidae | 0 | 1 | 2 | 0 |
| Bethylidae | 0 | 1 | 0 | 0 |
| Braconidae | 1 | 2 | 4 | 1 |
| Brrhidae | 0 | 0 | 0 | 1 |
| Byturidae | 0 | 0 | 1 | 0 |
| Calliphoridae | 0 | 0 | 1 | 0 |
| Cantharidae | 3 | 8 | 63 | 47 |
| Carabidae | 62 | 53 | 26 | 87 |
| Cecidomyiidae | 8 | 1 | 4 | 3 |
| Ceraphronidae | 2 | 12 | 2 | 19 |
| Ceratocombidae | 0 | 5 | 1 | 7 |
| Chloropidae | 3 | 5 | 2 | 14 |
| Chrysomelidae | 0 | 0 | 0 | 1 |
| Cicadellidae | 1 | 2 | 4 | 5 |
| Cicindelidae | 0 | 1 | 0 | 0 |
| Clubonidae | 0 | 0 | 2 | 0 |
| Coccinellidae | 1 | 1 | 0 | 0 |
| Corylophidae | 1 | 0 | 12 | 6 |
| Curculionidae | 0 | 0 | 0 | 1 |
| Cydnidae | 0 | 0 | 6 | 1 |
| Delphacidae | 2 | 0 | 0 | 4 |
| Diapriidae | 15 | 3 | 3 | 12 |
| Dolichopodidae | 2 | 1 | 0 | 2 |
| Drosophilidae | 0 | 6 | 2 | 4 |
| Ectobiidae | 1 | 0 | 0 | 0 |
| Elateridae | 10 | 2 | 6 | 6 |
| Encyrtidae | 0 | 0 | 0 | 1 |
| Ephydridae | 1 | 0 | 2 | 3 |
| Erotylidae | 3 | 13 | 11 | 27 |
| Eurytomidae | 0 | 0 | 1 | 0 |
| Figitidae | 2 | 6 | 3 | 15 |
| Formicidae | 470 | 740 | 902 | 594 |
| Gryllidae | 184 | 943 | 468 | 965 |
| Gryllotalpidae | 0 | 0 | 0 | 1 |
| Halictidae | 0 | 2 | 0 | 0 |
| Henicopidae | 5 | 22 | 13 | 14 |
| Histeridae | 11 | 5 | 2 | 9 |
| Hybotidae | 0 | 2 | 0 | 0 |
| Hydrophilidae | 4 | 2 | 4 | 0 |
| Ichneumonidae | 0 | 1 | 0 | 0 |

| | | | | |
|---|---|---|---|---|
| Lampyridae | 0 | 0 | 0 | 1 |
| Latridiidae | 3 | 10 | 13 | 4 |
| Limoniidae | 1 | 7 | 1 | 5 |
| Linyphiidae | 34 | 52 | 48 | 51 |
| Lycosidae | 50 | 71 | 164 | 99 |
| Megaspilidae | 0 | 1 | 0 | 0 |
| Miridae | 2 | 0 | 7 | 2 |
| Monotomidae | 1 | 4 | 4 | 8 |
| Mutillidae | 5 | 3 | 2 | 1 |
| Mycetophagidae | 0 | 5 | 10 | 0 |
| Mymaridae | 5 | 9 | 11 | 34 |
| Nitidulidae | 21 | 82 | 16 | 165 |
| Noctuidae | 0 | 3 | 0 | 0 |
| Pentatomidae | 2 | 2 | 7 | 9 |
| Phalacridae | 1 | 2 | 2 | 0 |
| Phoridae | 26 | 34 | 30 | 47 |
| Platygastridae | 2 | 1 | 0 | 0 |
| Poleniidae | 0 | 0 | 2 | 0 |
| Pompilidae | 2 | 0 | 3 | 2 |
| Pteromalidae | 0 | 5 | 1 | 1 |
| Reduviidae | 0 | 1 | 0 | 4 |
| Rhyparochromidae | 7 | 54 | 19 | 99 |
| Salticidae | 3 | 1 | 1 | 0 |
| Sarcophagidae | 0 | 7 | 0 | 0 |
| Scarabaeidae | 21 | 30 | 53 | 31 |
| Scatopsidae | 1 | 0 | 0 | 0 |
| Scelionidae | 171 | 555 | 211 | 382 |
| Sciaridae | 11 | 2 | 42 | 7 |
| Scoliidae | 1 | 0 | 0 | 0 |
| Silvanidae | 1 | 5 | 15 | 17 |
| Sphaeroceridae | 6 | 14 | 5 | 9 |
| Sphecidae | 1 | 1 | 0 | 0 |
| Staphylinidae | 46 | 108 | 136 | 219 |
| Tenebrionidae | 6 | 4 | 3 | 1 |
| Tetrigidae | 0 | 0 | 0 | 1 |
| Tettigoniidae | 0 | 0 | 0 | 1 |
| Theridiidae | 2 | 0 | 0 | 0 |
| Thomisidae | 0 | 1 | 0 | 0 |
| Thripidae | 0 | 6 | 0 | 17 |
| Thyreocoridae | 0 | 0 | 0 | 1 |
| Tipulidae | 0 | 0 | 3 | 0 |
| Ulidiidae | 1 | 0 | 0 | 0 |

**Table S20. Taxon Totals – Bee Bowls Traps Red Clover 2020**

| Genus | Species | Treatment | | | |
|---|---|---|---|---|---|
| | | CT | NT | LMFR | LMRye |
| *Andrena* | *imitatrix/morrison* | 0 | 0 | 0 | 1 |
| *Agapostemon* | *splendens* | 1 | 0 | 0 | 0 |
| *Agapostemon* | *texanus* | 0 | 1 | 0 | 0 |
| *Agapostemon* | *virescens* | 3 | 5 | 2 | 0 |
| *Apis* | *mellifera* | 1 | 2 | 1 | 1 |
| *Eucera* | *bamata* | 26 | 12 | 19 | 9 |
| *Halictus* | *ligatus/poeyi* | 0 | 0 | 5 | 2 |
| *Halictus* | *parallelus* | 1 | 6 | 1 | 4 |
| *Lasioglossum* | *callidum* | 0 | 0 | 0 | 1 |
| *Lasioglossum* | *coreopsis* | 0 | 1 | 0 | 1 |
| *Lasioglossum* | *hitchensi* | 0 | 0 | 0 | 1 |
| *Lasioglossum* | *leucocomus* | 0 | 1 | 0 | 1 |
| *Lasioglossum* | *leucocomus/pilosum* | 0 | 0 | 0 | 2 |
| *Lasioglossum* | *pilosum* | 3 | 0 | 2 | 2 |
| *Lasioglossum* | *trigeminum* | 0 | 0 | 1 | 0 |
| *Melissodes* | *bimaculatus* | 1 | 0 | 0 | 0 |

**Table S21. Taxon Totals – Bee Bowls Traps Red Clover 2021**

| Genus | Species | Treatment | | | |
|---|---|---|---|---|---|
| | | CT | NT | LMFR | LMRye |
| *Agapostemon* | *splendens* | 0 | 0 | 0 | 1 |
| *Agapostemon* | *texanus* | 0 | 0 | 1 | 0 |
| *Agapostemon* | *virescens* | 2 | 1 | 0 | 0 |
| *Apis* | *mellifera* | 2 | 1 | 0 | 0 |
| *Augochlora* | *pura* | 0 | 0 | 0 | 1 |
| *Augochlorella* | *aurata* | 1 | 0 | 0 | 0 |
| *Bombus* | *bimaculatus* | 1 | 0 | 0 | 1 |
| *Eucera* | *hamata* | 2 | 0 | 0 | 0 |
| *Halictus* | *ligatus/poeyi* | 3 | 3 | 2 | 0 |
| *Halictus* | *parallelus* | 2 | 0 | 3 | 2 |
| *Lasioglossum* | *bruneri* | 3 | 0 | 0 | 0 |
| *Lasioglossum* | *leucocomus* | 1 | 0 | 0 | 0 |
| *Lasioglossum* | *nelumbonis* | 1 | 0 | 0 | 0 |
| *Lasioglossum* | *pilosum* | 1 | 2 | 0 | 1 |
| *Lasioglossum* | *trigeminum* | 0 | 0 | 0 | 1 |
| *Melissodes* | *bimaculatus* | 5 | 5 | 2 | 0 |

**Table S21. Taxon Totals – Bee Bowls Traps Sweet Corn 2020**

| Genus | Species | Treatment | | | |
|---|---|---|---|---|---|
| | | CT | NT | LMFR | LMRye |
| *Agapostemon* | *splendens* | 0 | 2 | 0 | 2 |
| *Agapostemon* | *texanus* | 3 | 2 | 9 | 1 |
| *Agapostemon* | *virescens* | 9 | 18 | 8 | 12 |
| *Apis* | *mellifera* | 2 | 2 | 2 | 0 |
| *Augochlora* | *pura* | 2 | 4 | 4 | 3 |
| *Augochlorella* | *aurata* | 2 | 1 | 1 | 0 |
| *Halictus* | *confusus* | 0 | 1 | 0 | 0 |
| *Halictus* | *ligatus/poeyi* | 2 | 1 | 2 | 3 |
| *Halictus* | *parallelus* | 0 | 1 | 2 | 0 |
| *Lasioglossum* | *bruneri* | 0 | 0 | 2 | 2 |
| *Lasioglossum* | *callidum* | 2 | 1 | 2 | 0 |
| *Lasioglossum* | *coreopsis* | 0 | 2 | 1 | 0 |
| *Lasioglossum* | *hitchensi* | 1 | 0 | 0 | 0 |
| *Lasioglossum* | *leucocomus* | 3 | 2 | 5 | 3 |
| *Lasioglossum* | *leucocomus/pilosum* | 0 | 0 | 1 | 0 |
| *Lasioglossum* | *modestus/affinis* | 2 | 0 | 0 | 0 |
| *Lasioglossum* | *nelumbonis* | 0 | 0 | 0 | 0 |
| *Lasioglossum* | *pilosum* | 5 | 11 | 24 | 17 |
| *Lasioglossum* | *puteulanum* | 0 | 1 | 0 | 0 |
| *Lasioglossum* | *tegulare* | 0 | 0 | 0 | 1 |
| *Lasioglossum* | *trigeminum* | 0 | 2 | 1 | 1 |
| *Melissodes* | *bimaculatus* | 78 | 62 | 59 | 62 |

**Table S22. Taxon Totals – Bee Bowls Traps Sweet Corn 2021**

| Genus | Species | Treatment | | | |
|---|---|---|---|---|---|
| | | CT | NT | LMFR | LMRye |
| *Agapostemon* | *splendens* | 5 | 10 | 8 | 5 |
| *Agapostemon* | *texanus* | 6 | 7 | 17 | 8 |
| *Agapostemon* | *virescens* | 27 | 31 | 19 | 23 |
| *Apis* | *mellifera* | 14 | 10 | 9 | 12 |
| *Augochlora* | *pura* | 8 | 6 | 8 | 7 |
| *Augochlorella* | *aurata* | 3 | 3 | 1 | 2 |
| *Augochloropsis* | *sumptuosa* | 0 | 0 | 1 | 0 |
| *Bombus* | *sp.* | 3 | 0 | 0 | 0 |
| *Eucera* | *hamata* | 1 | 0 | 1 | 0 |
| *Halictus* | *confusus* | 1 | 1 | 0 | 0 |
| *Halictus* | *ligatus/poeyi* | 3 | 1 | 0 | 4 |
| *Halictus* | *parallelus* | 1 | 4 | 5 | 1 |
| *Lasioglossum* | *bruneri* | 8 | 2 | 6 | 5 |
| *Lasioglossum* | *callidum* | 2 | 3 | 3 | 0 |
| *Lasioglossum* | *coreopsis* | 0 | 2 | 1 | 0 |
| *Lasioglossum* | *cressonii* | 0 | 1 | 0 | 0 |
| *Lasioglossum* | *hitchensi* | 3 | 1 | 0 | 0 |
| *Lasioglossum* | *leucocomus* | 6 | 4 | 9 | 6 |
| *Lasioglossum* | *leucocomus/pilosum* | 0 | 0 | 3 | 1 |
| *Lasioglossum* | *modestus/affinis* | 2 | 0 | 0 | 0 |
| *Lasioglossum* | *nelumbonis* | 2 | 0 | 0 | 1 |
| *Lasioglossum* | *oblongum* | 0 | 1 | 0 | 0 |
| *Lasioglossum* | *pilosum* | 24 | 22 | 45 | 21 |
| *Lasioglossum* | *puteulanum* | 1 | 1 | 0 | 0 |
| *Lasioglossum* | *quebecense* | 0 | 0 | 1 | 0 |
| *Lasioglossum* | *tegulare* | 1 | 0 | 0 | 1 |
| *Lasioglossum* | *trigeminum* | 3 | 4 | 4 | 2 |
| *Melissodes* | *bimaculatus* | 79 | 48 | 62 | 28 |
| *Melissodes* | *denticulata* | 0 | 0 | 0 | 1 |
| *Peponapis* | *pruinosa* | 0 | 0 | 0 | 1 |

**Table S23. Taxon Totals – Pollinator Observations Red Clover**

| Order | Observation Group | Observation Year | |
|---|---|---|---|
| | | 2020 | 2021 |
| Lepidoptera | Brushfoot | 140 | 86 |
| | Gossamer | 13 | 25 |
| | Monarch | 2 | 15 |
| | Skipper | 262 | 391 |
| | Swallowtail | 1 | 7 |
| | White/Sulfur | 114 | 134 |
| Hymenoptera | Carpenter bee | 8 | 38 |
| | Bumblebee | 673 | 330 |
| | Honeybee | 163 | 148 |
| | Large dark bee | 12 | 14 |
| | Long horned bee | 4 | 1 |
| | Metallic bee | 4 | 5 |
| | Small dark bee | 0 | 0 |

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