ASSESSING BIODIVERSITY IN SUMMER COVER CROP ROTATIONS FOR BENEFICIAL ARTHROPOD CONSERVATION

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

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May 2022

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ACKNOWLEDGEMENTS

I am but a single drop in a moving sea. The movement and work needed to complete a thesis is only possible by the actions of many. My work has been guided, informed, and encouraged by numerous colleagues, friends, and family throughout my journey. I would like to especially thank the following people for their intellectual and emotional contributions to the work presented in my thesis:

Dr. Mary Rogers: My co-advisor, who introduced me to a new world of wonders, the entomology world, to which I feel in love. Thank you for being my mentor in LSSURP and opening the doors for me to keep advancing as an academic. Your support and understanding throughout my master's degree always uplifted and encouraged me to keep working harder.

Dr. Julie Grossman: My co-advisor, who always motivated me to push pass my limits. Thank you for always challenging me to think outside the box, for being so joyful and inclusive, and for going above and beyond to make our lab as outgoing and organized as it is.

Dr. Adria Fernandez, Gabriela Hidrobo, and Ezra Moses: My collaborative research team, Dr. Adria Fernandez for organizing and directing our work to be accomplished successfully, Gabriela Hidrobo for your help, kindness, and friendship in and outside the project, and Ezra Moses for inspiring me with your hard work and intelligence and providing assistance in the statistical analysis.

Pippa Dobbyn, Joe Nelsen, Tali Berkman, and Jay DeLacy: The star assistants in my entomology research. All of you were key in my capacities to accomplish this thesis. Thank you for all the hot and sunny days spent with me counting flowers and insects, taking soil samples, collecting biomass, helping me organize myself and processing samples with me. I hope this was an enriching experience for you as much as it was for me and that you learn and honed new skills in the process.

Dr. Anh Tran, Nathan Hecht, Matthew Gullickson, Claire Hodge, Christina Perez, Leah Worth, Amanda Reardon, Molly Farrell, and Erika Christiansen: The Rogers Lab crew, you were all such great lab mates and friends, thank you for always lending a helping hand with studies, research, and graduate life, I appreciate all of you deeply. Especially Dr. Anh Tran, thank you for always brightening up my day with your jokes and your authentic and genuine self, you are a true inspiration. I also want to thank you for always being so willing to help me with my statistical analysis inquiries and formatting many of my final publish figures.

Dr. Vivian Wauters, Dr. Sharon Peronne, Rebecca Fudge, Dr. Miriam Gieski, Anne Pfeiffer, Dr. Thanwalee "JiJY" Sooksa-nguan, Marie Schaedel, Alex DeRusha, Bonsa Mohamed, Tanner Beckstrom, Mar Horns, Sarah Duber, Zala Čok, Ada Fitz-Axen, Isaiah

Curtis, and Magdalena: The Grossman lab crew, such a varied group of talented, hard-working, intelligent, and culturally-diverse people. It was an honor to work, collaborate and share spaces with each and one of you. You all thought me so much about yourselves and I am truly grateful for that. Especially Dr. Vivian Wauters for being such a big help in guiding my work and making me feel included in our lab, you are such a compassionate and caring person. Dr. Sharon Perrone for inspiring me to be as hard working and over-achiever as you and for providing assistance in the statistical analysis, thank you for always being so thoughtful and sharing your art and passions with me, and Rebecca Fudge, I am so grateful to have been in your cohort and witness your charisma. Thank you for always making the lab feel so light and fun, you always put a smile on my face.

Dr. Ralph Hozenthal and Jessica Miller: My committee member, Dr. Ralph Hozenthal for being such a great taxonomy professor, your passion and intelligence for entomology and taxonomy was a truly inspiring. Thank you for helping me verify my arthropod samples, as well as Jessica Miller.

Sarah Foltz, Karin Jokela, and the Xerces Society: Our research collaborators for providing the necessary tools and knowledge to make our entomology research a success. Especially Sarah Foltz for providing three workshops on observational bee identification for me, as well as for our community partners to identify bees and other insects observationally in the field. Thank you for also being so passionate with your work and a friend to me.

Hailey Shanovich: First and foremost, thank you for your friendship, you are such a lovely, understanding, and caring friend. Thank you for also providing me with the diversity analysis codes and being so willing to discuss any statistical inquiries. You helped me so much in and out of graduate school and I will forever cherish you.

Steve Ziertman and custodial staff: Thank you to Steve Ziertman for being so willing, available, and friendly to always help me fix field equipment and to the custodial staff for keeping our department clean and safe during COVID spread.

Molly Schaus, KaZoua Berry, and Big River Farms community: Thank you to our research community collaborates for creating alliances with our lab and keeping our research plots cleaned and maintained.

Zac Paige, Adam Woltjer, and the White Earth community: Thank you to our research community collaborates for opening your trust to our university and our lab and permitting us to work in your sacred land, to which I have the upmost respect. Especially I would like to thank Zac Paige and Adam Woltjer for maintaining our plots and helping me collect insect and flower data.

Dr. Emily Hoover, CFANS and the Horticulture Department: Thank you for making it

financially possible for me to attend graduate school, without you I would not be here in the first place.

Classmates and professors: Thank you for all the knowledge, friendships and growth I was able to obtain because of all of you.

Friends, parents, family, and TerraNova Urbana: You were the biggest motivation for me to keep working hard and accomplish my dreams, thank you for your support, love, dedication, and trust in me.

DEDICATION

I would like to dedicate this work to my mother, Yolanda Morales Alfonzo, who has always given so much of her time and energy for me to accomplish my goals. Thank you for being my role model to be a strong and independent woman, for giving me your support and unconditional love, and for always believing in my dreams.

ABSTRACT

Intensive vegetable crop practices can have detrimental effects on soil health, draining soil of organic matter reserves and necessitating nitrogen (N) inputs. These amendments can support crop productivity but may have considerable environmental consequences including overfertilization, water eutrophication, and reduce fauna (Agostini et al., 2010). In addition, many vegetable crop rotations are characterized by high plant density but low beneficial arthropod and pollinator habitat diversity (Carreck and Williams, 2001). Habitat simplification may cause declines in beneficial arthropods, which can lead to insufficient pollination services and increased pest pressure (Hogg et al., 2011; Wilson et al., 2018). Out of numerous arthropod services, pollination, pest control, dung burial and wildlife nutrition have been estimated to value at least $57 billion USD (Forister et al., 2019). Because of sheer amount of agricultural land, comprising over 40% of all U.S. land, agricultural ecosystems present valuable opportunity in maintaining biodiversity (USDA, 2012). Constant forage availability from early spring to late summer is particularly imperative for the survival of social insects with long-lived colonies, such as bees (Carreck and Williams, 2001). The use of cover crops can expand the seasonal availability of floral resources in agroecosystems (Hooks et al. 1998; Landis et al. 2005). In a two-part study, this research investigated the effects of summer-planted cover crops on soil nutrient contributions and beneficial arthropod density, diversity, richness and evenness. Part one consisted of a one-year (2019) field trial study where nine treatments, each containing one to seven species of cover crops, were evaluated for flowering, aboveground biomass production and nitrogen (N) content, soil-N contribution after

biomass incorporation, and beneficial arthropod visitation. A seven-species mix composed of oat (*Avena sativa* L.), field pea (*Pisum sativum* subsp. Arvense L.) and 5 clover species (*Trifolium* spp.) added the largest amount of biomass (8747 kg/ha). Likewise, this mix contributed the most organic N (265.6 kg N/ha) and maximum soil -N subsequently increased after biomass incorporation (10.9 mg -N/kg of soil). Part two consisted of a two-year (2020-2021) study evaluating the ability of two rotational systems of summer cover crop species, selected from 2019 trials, to provide key multifunctional ecosystem benefits to vegetable crop production. The first system was an early cover crop planting followed by a broccoli cash crop, and the second system consisted of an early planting of spring lettuce followed by a late summer cover crop planting. In all three years, buckwheat (*Fagopyrum esculentum* Moench) and phacelia (*Phacelia tanacetifolia* Bendth.) monoculture produced most abundant floral resources. Beneficial arthropods observed included pollinators (native, honey and bumblebees), predators (syrphid flies and minute pirate bugs), and parasitoids. Increased floral diversity was associated with abundance of flies in the family Syrphidae. Phacelia monoculture was most attractive for bees in the families Apidae and Halictidae, both of which may provide pollination services. These results highlight floral visitation patterns as an indicator for beneficial arthropod community support and conservation. Summer-planted cover crops are an underexplored rotation option for organic farming systems in the Upper Midwest and may support a wide range of ecosystem services including increases in available soil N and beneficial arthropod services.

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CHAPTER 1 – LITERATURE REVIEW: SUMMER COVER CROP OPTIONS AS ECOSYSTEM SERVICE TOOLS IN ORGANIC VEGETABLE FARMS OF THE UPPER MIDWEST

In response to growing population demands, many intensive vegetable systems have increased ecological instability by reducing organic matter reserves and biodiversity through intensification (Pulleman et al., 2000; Tilman et al., 2002). These ecological imbalances promote greater fertilizer and pesticide external input needs, which only temporarily address the issue and may have considerable environmental consequences including overfertilization, water eutrophication, and reduce fauna (Agostini et al., 2010). Moreover, high-external input-based practices have contributed to greater soil degradation and erosion, with soil infertility as a major outcome (Vanwalleghem *et al*., 2017).

Though some associate greater yields with high external inputs, including conventional fertilizers (Kirchmann et al., 2007), modern agricultural practices, likewise, increase erosion at a parallel rate (Mazoyer and Roudart, 1997; Tilman, 1998). Furthermore, extended flood and drought periods caused by climate change, no longer make these management practices sustainable options. Conversely, organic farming can increase soil organic matter (SOM), enhancing soil structure and stability. Research has shown topsoil increases up to 16 cm and 3 cm at surface horizon (Reganold et al., 1987). Organic farming practices can also be more accessible and sustainable, providing an opportunity to use cost-free, environmental resources at hand.

Natural vegetation patterns have also been greatly affected by land management, having a substantial influence on pollinators and beneficial arthropods, which are dependent on their surrounding environments to acquire forage and nesting spaces (Kaplan *et. al*, 2010). In an agronomic sense, beneficial arthropods refer to any species that contributes to the conservation, protection and enhancement of an agronomic crop and farming system (Landis et al., 2005). Intensive vegetable systems that lack diversified floral resources are low in biodiversity and habitat for beneficial insects. The lack of habitat and food resources has contributed to wild pollinator decline (O'Conner, 2013). Herbicide use has decreased vegetation from which pollinators and beneficial arthropods acquire nutrition, inherently affecting organism populations (Carreck and Williams, 2001), but also, through pesticide use many beneficial arthropod species have been decreasing at a rapid pace (Rusch et al., 2010; Forister et al., 2019). Due to high specificity in arthropod food source selection, it is critical to include diverse floral resources throughout the year (O'Conner, 2013). Constant forage availability from early spring to late summer is particularly imperative for the survival of social insects with long-lived colonies, such as bees (Carreck and Williams, 2001). The use of cover crops can expand the seasonal availability of floral resources in agroecosystems (Hooks et al. 1998; Landis et al. 2005).

Cover crops are defined as any vegetation that is mainly used to protect the soil from erosion and degradation, and can also provide a variety of other ecosystem services, including increased floral resources, weed control, soil fertility, soil moisture

conservation, increased soil organic matter, and decreased water contamination through reduced nutrient leaching and runoff (Reicosky and Forcella, 1998; Fageria et al., 2005; Campbell et al., 2006; Blanco-Canqui et al., 2015; Bulan et al., 2015; Sharma et al., 2018). Through the provision of these services, humans can benefit from an indirect economic return by reducing the need for external inputs, while simultaneously increasing soil fertility and maintaining or improving the quality of cash crops. Including cover crops in rotation systems can be a pragmatic way of increasing diversity and can be integrated in many divergent cropping systems (Creamer and Baldwin, 2000; Finney & Kaye, 2017; Blesh et al., 2019). However, while the broad patterns are known, important details for diversifying agroecosystems, including the capacity to provide multifunctionality using cover crops in rotation systems are yet to be fully understood. (Creamer and Bennett, 1997; Schipanski et al., 2014; Daryanto *et al*., 2018).

Cover Crop Management for Organic Vegetable Production in the Upper Midwest

Cover crops can be planted between crop beds, integrated in an intercropping system as a living mulch and/or established in fallow areas between crop rotations (Nicholls & Altieri, 2013). Farmers typically sow cover crops during fallow periods. Rotating with cover crops is a requirement in organic farming. Nonetheless, both conventional and organic farmers include cover crops in their rotation systems, achieving better management of resources (SARE, 2020.) Therefore, it is important to have research to provide recommendations for integrating cover crops in different regions and climates.

The planting season in the Upper Midwest is shorter compared to less temperate and tropical regions because of extreme cold weather, with an average temperature ranging from -13 °C to 1 °C between December and February (NOAA, 2013). For this reason, farmers in the Upper Midwest are constantly looking for ways to increase land use efficiency. Despite this short growing season, usually extending from May to late October, annual vegetable crops provide rotational flexibility in crop varieties, including cool and warm season crops that grow during different portions of the short season. These rotational systems integrated with cover crops can potentially provide ecosystem services, improving cash crop productivity and indirectly increasing economic returns over the long term (Clark, 2013). For example, living cover crops have been shown to reduce nutrient leaching in vegetable production systems, which affects environmental stability and pollution (Campbell et al., 2006; Agostini, 2010; Kaye et al., 2019). An economic analysis of cover crops on farms participating in the southeastern Minnesota Cover Crop and Soil Health Initiative showed cover crop planting and termination can involve a significant cost for these producers. However, cover crops also reduced soil erosion and increased soil organic matter, potentially contributing to yield improvements (Lazarus and Keller, 2018).

Determining Utility of Cover Crops

Cover crops provide a wide range of ecosystem services, including nitrogen (N) addition for subsequent cash crops, weed suppression, topsoil protection, floral resource addition, among others (Sarrantonio, 2007). Selecting primary service acquisitions will determine

cover crop management. As with other crops, cover crops will be highly dependent on their growing requirements, including light, temperature, and water needs, sowing time and density, and species combinations (Florentin et al., 2010). The most common farmer practice is planting a single cover crop species, but mixes can also provide combined benefits (Magdoff and Van Es, 2009). Planting mixes of legumes and grasses can result in higher levels of fixed atmospheric nitrogen (Creamer and Baldwin, 2000). Grasses have quicker and deeper root system establishment than legumes. This root system increases soil nitrogen uptake and results in lower soil nitrogen availability, stimulating legume nodulation and N_2 fixation (Giller and Cadisch, 1995). Other mixes may include grain varieties or in combination with legume or radish.

Management considerations include cover crop termination and tillage (Blanco-Canqui et al., 2015). These management decisions potentially promote beneficial services including increased organic matter reserves and nutrients and prevent cover crops from becoming weeds in subsequent rotations (Magdoff and Van Es, 2009; Clark, 2013). Farmers usually plant cover crops after cash crop harvest, primarily to avoid competition.

Rotations and Termination of Cover Crops

Planting time is based on desired cover crop goals. Cover crops in the Upper Midwest region can be grown during a full season to fertilize soil and add organic matter. They can also be integrated after an early season vegetable is harvested (sown between early May-late June), and grown for a short season (sown late June-early August), or followed by a late season crop (sown mid-August-late October). However, the window between

cover crop termination and a late season cash crop planting can sometimes be too short, decreasing cash crop yields (Wauters et al., 2021). A second way to extend cover crop benefits is to eliminate a cash crop rotation from the planting year. Adding cover crops after harvesting a spring-planted cash crop, or prior to a summer-planted cash crop may help overcome yield barriers. Some farmers may find this window unattractive since it eliminates the potential planting of a cash crop. Others may find that the indirect economic value provided by cover crop ecosystem services are sufficient and essential for optimal ecosystem functioning, of which a cash crop is highly dependent. Land-space rotations and fallow periods may provide opportunities to add cover crops and maintain typical cash crop plantings.

Regardless of temporal and spatial cover crop rotations, termination and, most likely, cover crop tillage are important management considerations. Adequate cover crop termination time prevents over maturity and seed filling to avoid cover crop weed establishment and adds soil nutrient and organic matter (Parr et al., 2011). Mowing cover crops can increase decomposition rates by exposing a greater surface area to soil microbes (Liebman et al., 2018). Reduced or no-till approaches may be combined with cover crop termination, as greater soil conservation benefits may be acquired (Daryanto et al., 2018). However, reduced or no-till applications can increase N immobilization by increasing accumulated cover crop carbon inputs (Nevins et al., 2021).

Cover Crop Provision for Certified Organic Requirements

Cover crop agroecological benefits are critical components of certified organic systems, which have been increasing over the last few years. In 2016 organic farmland increased globally to 57.8 million hectares (Willer et al., 2018). In the United States (US) organic management reached 2 million hectares and sales expanded from 15 to 90 billion dollars in the last two decades (Willer et al., 2018). Globally, the US has the largest market of organic food and non-food products with 47% and almost 44 billion US dollar sales in 2016 and 62 billion in 2020 (Willer et al., 2018; McNeil, 2021). The increased interest in organic systems and sustainable practices are largely tied to the environmental crisis (Duruiheoma et al., 2015). Landscape simplification, resource contamination, biodiversity depletion and soil degradation are major outcomes of high external input-based farming. Modern agricultural techniques have led to consumer concern about food development and quality (Dimitri, 2010; Vogl, 2015).

Cover crops can satisfy organic production requirements including organically sourced nutrients, minimized external fertilizer inputs, weed control, increased beneficial arthropod visitation, decreased pesticide use, soil surface protection, and build and maintain soils through organic matter addition (Parr et al. 2011; Schipanski et al., 2014; Blesh, 2017, 2019). As a result, significant external input cost decreases with increased cover crop system efficiency (Snapp et al., 2005).

Ecosystem Services: Soil Property Contributions

In northern parts of the world, such as the Upper Midwest, winter cover cropping is a common management practice. Some species used by farmers are oats (*Avena sativa*), winter rye (*Secale cereale* L.), hairy vetch (*Vicia villosa* R.) and oilseed radish (*Raphanus sativus* L.). Cover crops are integrated primarily to reduce nutrient leaching from excess fertilizer application and decomposed organic residue. Above and below ground biomass absorbs N and water that would otherwise be lost through percolation. While winter cover crops can decrease leaching, cover crop species possess different soil nutrient uptake capacities. Grasses, compared to legumes, are better N scavengers. Kramberger et al. (2009) compared grass and legume soil N mineralization (Nmin) and concluded lower soil Nmin content in grasses, while both exhibited lower soil Nmin than control plots. Wyland et al. (1996) stated cover crop capacity (*Phacelia tanacetifolia* cv. 'Phaci', and *Secale cereale* cv. 'Merced') to reduce 65-70% nitrate leaching when compared to a bare plot.

Another benefit of winter cover crops is soil surface protection. Soil erosion has been problematic since the beginning of agriculture, and heavy machinery and centralized external input management has rapidly advanced soil erosion. Lal (2003) estimated 1094 million ha eroded at a global scale and 751 million ha heavily eroded. Erosion via water is one of the major losses of topsoil in the world. Above ground plant biomass reduces the impact of water before it reaches the soil surface, while the root system can hold soil

in place and creates porosity for water filtration and absorbance (Sumiahadi et al., 2019). Parlak (2016) determined significant differences in time to runoff from plots with cover crops (*Vicia faba* L. and *Vicia sativa* with *Triticum aestivum* -72.50 s) than bare plots (27.75 s). Cover crops have the capacity to easily reduce runoff, preventing a major cause for water erosion.

Symbiotic dinitrogen legume fixation is of primary interest to farmers (Blesh, 2017), as cover crops can contribute new nitrogen to the system. N surplus is described as the sum of N inputs (organic and conventional fertilizer, biological N fixed and depositions) minus the N outputs (N used by crops) (Zhang et al., 2015). These surpluses promote N leaching and contaminate other ecosystems (Blesh and Drinkwater, 2013). Fields with added legume N and crop rotations create less surplus and greater soil nitrogen balance compared to fertilizer-based practices (Blesh and Drinkwater, 2013). Legume-fixed nitrogen also depends on soil fertility. Reduced fixed nitrogen may occur if soil nitrogen pools satisfy legume nitrogen needs, limiting symbiotic relationships with rhizobia bacteria due to high energy carbon provision costs to symbiotic partners (Kiers et al., 2003). Legume species fix N at different rates, and when combined in mixes with grasses, legumes can be encouraged to fix more nitrogen, mainly due to grasses' competitiveness for soil nitrogen (Jensen, 1996).

A challenge presented by winter cover crops is spring planting disruption, as farmers claim the window between cover crop tillage and cash crop planting is very short

(Wyland et al., 1996). However, cover crop transpiration reduces moisture, potentially advancing cover crop tillage (Wyland et al., 1996). Ease of management, as cover crops grow at a slower pace, and longer fallow periods make Upper Midwest winter cover cropping a commonly adopted practice. However, implementing summer-planted cover crops can potentially provide greater ecosystem services in the summer months. Summer cover crops are grown during peak production season. Due to food production intensification, increasing tillage and inputs, many soils are nutrient deficient and eroded. Summer cover crops can fill gaps in between cash crop rotations that can potentially rebuild fertility and soil structure. Like any winter cover crop, summer cover crops can be used as N source for successive crops, mitigate weed pressure and nutrient leaching, regenerate soil by increasing soil organic matter and enhance soil structure (Creamer & Baldwin, 2000). Regardless of season, farmers are constantly dependent on ecosystem services that conserve and generate resources to sustain crop production.

Ecosystem Services: Floral Resources for Beneficial Arthropods

Although cover crops generally have potential to provide these services, some more than others, in the Upper Midwest, summer cover crops may also produce floral resources. Flowers are an essential part for supporting and maintaining pollinators and natural enemies, which can provide pollination and biological control services. Around 35% of globally produced crops, including 800 cultivated plants, depend on animal pollination (Nicholls & Altieri, 2013). Globally, pollination services have been estimated to be over $200 billion dollars annually (Gallai et al., 2009). Floral resources provide a significant

amount of nutrition for predators, parasitoids and pollinators (Wäckers et al., 2005). Parts of the flower, including pollen, nectar and sap are used by pollinators and natural enemies, especially when prey is scarce (Landis et al., 2005). Besides being a preferred host plant for many wasps and bees (Carreck and Williams, 2001; Hogg et al., 2011), borders of phacelia explored in cabbage fields increased presence of syrphid flies, while aphid populations declined (Landis et al., 2000). Summer cover crops can also supply nesting habitats (Blaauw & Isaacs, 2014). These cover cropping resources are sometimes deficient in agricultural landscapes where increased tillage and herbicides reduce plant diversity (Hogg et al., 2011). Planting summer cover crops to diversify agroecosystems can positively impact beneficial arthropod populations. Adding flowering cover crops can increase diversity and abundance of wild bees and other pollinators (Wilson et al., 2018; Hecht, 2019).

Different flower species receive diverse arthropod visitation. Flowers have become more specialized and arthropods more selective of floral resources through coevolution (Nicholls & Altieri, 2013). Research has positively correlated bee species abundance in a given landscape with plant species diversity, and flowering vegetation areas relative to bare plots (Banaszak, 1996). In North America, bee population declines associated with industrial agricultural methods, including habitat degradation and pesticide applications, have accelerated since 2004 (Nicholls & Altieri, 2013). Mass monoculture farming may limit food and habitat resources and disrupt plant-insect interactions (Blaauw & Isaacs, 2014). Homogeneous fields also tend to bloom simultaneously, providing scavenging

pollinators shorter resource availability (Nicholls & Altieri, 2013). Nafziger and Fadamiro (2011) showed buckwheat (Fagopyrum esculentum Moench), a commonly used cover crop throughout the US, increased female and male wasp, *Microplitis croceipes* (Cresson) (Hymenoptera: Braconidae), lifespan by at least two-fold relative to wasps supplied with water only. Summer cover crops can supplement resource diversity and conserve beneficial arthropod populations. Besides direct contributions to beneficial arthropods, including pollen or nectar, cover crops provide indirect benefits by supporting alternate hosts and moderating microclimate (Landis et al., 2005).

Cover cropping guidelines frequently recommend non-native annual plants to attain desired ecosystem services. However, some evidence shows native plants are better able to support beneficial arthropods (Fiedler and Landis, 2007; Isaacs et al., 2009). Annual plants can provide planting and flowering flexibility but hinder potential perennial habitat benefits, including natural enemy overwintering sites (Fiedler and Landis, 2007). Despite these arguments, diversity in floral morphology, physiology, phenology and farmers' intent for specific ecosystem services should be considered as well as nativity alone (Salisbury et al., 2015; Hecht, 2019). Critical cover crop considerations may enhance beneficial arthropod floral visitation. Plant species selections that provide greater benefit must consider specific landscape contexts and minimize competition with other cultivated areas.

Beneficial Arthropod Services vs Nitrogen Contribution

Cover crop management requires a complex balance of management strategies, including nutrient and water supply, crop protection, termination and tillage. These decisions are dependent on economic, environmental, time and resource limitations. Optimizing cover crop benefits and reducing trade-offs between ecosystem services can be a farmer challenge due to particular management requirements. For instance, when cover crops are tilled into the soil, nutrients may mineralize faster relative to no-till cover crops (Blanco-Canqui et al., 2015; Liebman et al., 2018). However, no-till systems may proliferate soil biota, including microbes (fungi and bacteria) and animals such as nematodes, mites, collembola, diplopoda, earthworms and arthropods, and their contributed ecological benefits (Altieri, 1999). Other trade-offs related to cover crop N contribution include termination timing. A maturing plant developing seed pods will mobilize nitrogen from roots, leaves, stems and flowers to developing pods (Schiltz et al., 2005). Therefore, to acquire greater organic nitrogen mineralization, cover crop termination must precede seed filling. Blooming flowers increase beneficial arthropod visitation, and may enhance ecosystem services including pollination, predation and parasitism (Nicholls and Altieri, 201; Philips et al., 2014). Conserving beneficial arthropod services requires floral resource extension and may increase potential nitrogen mobilization, as seed development occurs after floral pollination. Minimizing the information gap on cover crop species and suitable Upper Midwest management techniques will be imperative for reducing service trade-offs while increasing beneficial services, the overall goal of this

research.

Challenges of Implementation

Although cover crops are not commonly used as direct economic returns (marketable products), indirect economic revenue could be achieved. While beneficial and prejudicial economic outcomes of cover crops establishment are possible (Reicosky & Forcella, 1998), farmers and policy makers must consider direct and indirect benefits, production costs, risks, and agricultural policy (Bergtold et al., 2019). Farmers with sustainability, social empowerment and stewardship objectives may involve cover crops' social and environmental aspects in the overall deliberation. In many cases, cover crops are argued to be costly when considering seed cost, resource management, and labor (Scott et al., 1994; Clark, 2013; Olakunle, 2016; Bergtold et al., 2019). Conversely, cover crop ecosystem services provide considerable indirect economic returns. However, because these benefits are indirect and many times interrelated, it is challenging to determine financial value; particularly because they address benefits towards landowners and society. For example, soil organic matter (SOM) can benefit a farmer by increasing soil carbon (C) and nutrient content, moreover, society as a whole can benefit through mechanisms including C sequestration (Bergtold et al., 2019). Variables such as standing cover crops, yield, management, land type, equipment, weather and climate change can all determine overall profitability of cover crops. Continued use of cover crops year after year could stabilize benefits for improving soil health, system productivity and cost reduction. Substantial economic returns from cover crop implementation can be more

noticeable in the long-term (Keisling et al., 1994).

Research Objectives

Despite advantages provided by cover crops, farmer adoption rates are low. An estimated 18% of farmers in the US corn belt (Indiana, Illinois, Iowa, and Minnesota) have used cover crops in their farming system in the past (Singer et al., 2007). Wade et al. (2015) found that in 2010-2011, only 4% of farmers in the US had integrated cover crops in some parts of the farm such as field edges, but only 1.7% did so on cropland. This demonstrates the necessity of thoroughly understanding behavior, management practices, and cover crop ecosystem services to enhance adoption of cover cropping practices. Therefore, this research project explored 1) the viability of summer cover crops in rotations with organic vegetable crops, and 2) quantified ecosystem services, including N provision and beneficial arthropods visitation associated with flowering cover crops in the Upper Midwest.

CHAPTER 2–EXPLORING MULTIFUNCTIONALITY OF SUMMER COVER CROPS FOR ORGANIC VEGETABLE FARMS IN THE UPPER MIDWEST

Candelaria, N.P., 2022. Exploring multifunctionality of summer cover crops for organic vegetable farms in the Upper Midwest. *Renewable Agriculture and Food Systems*, 37(3): 1-8.

SUMMARY

Intensive vegetable crop rotations can have detrimental effects on soil health, draining soil of organic matter reserves and necessitating nitrogen (N) inputs. In addition, many vegetable crop rotations leave little time or space to integrate beneficial arthropod and pollinator habitat into crop rotations; the lack of habitat may cause declines in beneficial arthropods, which can lead to insufficient pollination services and increased pest pressure. Nine treatments, each containing one to seven species of cover crops, were evaluated for flowering, aboveground biomass production and N content, soil NO_3^--N contribution after biomass incorporation, and beneficial arthropod visitation. A seven-species mix composed of oat (*Avena sativa* L.), field pea (*Pisum sativum* subsp. *Arvense* L.) and 5 clover species (*Trifolium* spp.) added the largest amount of biomass (8747 kg/ha). Likewise, this mix contributed the most organic N (265.6 kg N/ha) and maximum soil NO_3^--N subsequently increased after biomass incorporation (10.9 mg NO_3^--N/kg of soil). Buckwheat (*Fagopyrum esculentum* Moench) and phacelia (*Phacelia tanacetifolia* Bendth.) monoculture produced most abundant floral resources. Beneficial arthropods observed included pollinators (native, honey and bumblebees), predators (syrphid flies and green lacewings), and parasitoids. Increased floral diversity was associated with abundance of flies in the family Syrphidae. Phacelia monoculture was most attractive for bees in the families Apidae and Halictidae, both of which may provide pollination services. These results highlight floral visitation patterns as an indicator for beneficial insect community support and conservation, especially in summer months, where greater

insect reproduction is undergone. Summer-planted cover crops are an underexplored rotation option for organic farming systems in the Upper Midwest, and may provide a wide range of ecosystem services including increases in available soil N and beneficial arthropod populations.

INTRODUCTION

Intensification of agricultural production systems can lead to natural resource depletion and reduced biodiversity. Although intensively managed agroecosystems can increase food production in the short term, longer term outcomes include loss of natural habitats and biodiversity of flora and fauna, water contamination, soil degradation and reduced capacity for crop productivity (Tilman et al., 2002; Zhang et al., 2015; Imadi et al., 2016). In particular, low-diversity rotations can lead to soil fertility imbalances and declines in beneficial arthropod habitat, indirectly affecting soil degradation and water pollution (Büchs et al., 1997; Pender and Mertz, 2006; O'Rourke et al., 2008; Bowles et al., 2020). Vegetable systems require high nutrient inputs for sustained yields, which may result in overfertilization and surface water eutrophication (Agostini et al., 2010). Simplification of these systems limits the availability and variety of floral resources in Midwestern farming landscapes (Wäckers et al., 2007; Blaauw and Isaacs, 2014; Forister et al., 2019). This, in turn, reduces the ability of the landscape to support beneficial arthropods (O'Connor, 2013).

Organic farming practices can reduce soil erosion and increase soil organic matter (SOM), thereby enhancing soil structure and stability (Pulleman et al., 2000; Leithold et al., 2014; Seitz et al., 2019). These outcomes are often achieved via the use of cover crops to meet certified organic system diversification requirements (NOP, 2021), presenting an opportunity for inclusion of a range of cover crops species that meet the dual goals of soil and beneficial insect habitat improvement. This is especially true in Upper Midwest vegetable systems, where a variety of short fallow periods exist between cropping cycles when cover crops could be integrated (Wauters at el., 2021). For example, cover crops could be established in spring, maturing during summer, and terminated prior to fall crop planting, or after an early spring cash crop, maturing throughout the late summer months. Upper Midwest summers are increasingly hot and humid with frequent rain events, which increase summer soil erosion and nutrient leaching (NOAA, 2013; Sumiahadi et al., 2019). For organic vegetable farmers in northern regions, cover crops planted during the summer months have the potential to reduce negative impacts of these climate shifts while increasing a range of ecosystem services, including production of aboveground biomass, biomass N, suppression of weeds, and floral resources for pollinators (Creamer and Baldwin, 2000; Wilson et al., 2018).

Cover crop species planted in the summer months, even in the coldest U.S. climates, could provide the multifunctionality needed to meet numerous agroecosystem goals. Cover crops supply critical nutrients to organic vegetable production (Parr et al., 2011; Schipanski et al., 2014; Blesh, 2017, 2019; Piotrowska-Długosz and Wilczewski, 2020).

They have been shown to contribute up to 300 kg N ha^{-} (Creamer and Baldwin, 2000; Fageria et al., 2005; Sarrantonio, 2007; Parr et al., 2011; Asik et al., 2020), and increase soil fertility through changes in physical, chemical and biological parameters (Drinkwater et al., 1998; Reicosky and Forcella, 1998; Daryanto et al., 2018). Moreover, when cover crop functional groups are combined, greater multifunctionality can be obtained (Finney et al., 2017; Kaye et al., 2019). For example, when legumes and grasses are combined, legumes may fix more N due to competition with grasses in acquiring soil N (Jensen, 1996; Høgh-Jensen and Schjoerring, 2001; Blesh, 2017). These crops also offer an opportunity to add floral resources throughout the growing season. Adding flowering cover crops to the rotation supports diversity and abundance of beneficial arthropods, including bees and natural enemies of pest (O'Connor, 2013; Redlich et al., 2018). These arthropods can provide ecosystem services to the farm, including pollination and predation and parasitism of pest (Hooks et al., 1998; Landis et al., 2005).

Data is scarce regarding the degree to which summer-planted flowering cover crops can support beneficial arthropod communities while simultaneously supporting soil health services, particularly soil nutrient cycling, in vegetable production systems. The objectives of this research were to assess possible contributions of 16 cover crop species and species mixes towards enhancement of 1) soil health factors (biomass production and C:N ratio content, NO_3^--N contributions) and 2) beneficial arthropod habitat (population abundance, diversity, and richness).

MATERIALS AND METHODS

Experimental Location and Treatments

A summer-planted cover crop trial was established in a single growing season from May to September 2019 at the University of Minnesota Agricultural Experimental Station (MAES), Twin Cities campus, St. Paul, MN (44.990829, -93.175832). Species were selected to represent commonly used Upper Midwest cover crops and their expected contribution of beneficial arthropod floral resources and nutrient cycling. Results from an on-farm preliminary trial and recommendations from the Xerces Society for Invertebrate Conservation and by farmer collaborators further supported species selection (Table 1). Regional mean annual rainfall is 813 mm, and the soil is classified as a Waukegan silt loam (Fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). Treatments were arranged in a randomized complete block experimental design with four replications, with each treatment plot measuring $3m^2$. Cover crops were broadcast sown at two dates (early and late), lightly raked to increase seed to soil contact, and terminated at the time of seed formation (Table 2). Previous fertility management prior to experiment establishment included historical manure additions, as well as regular additions of composted turkey litter. No synthetic or organic fertilizers and pesticides were applied in the two years prior to the experiment, or during the experimental growing season.

Biomass and Soil Sampling

Plant biomass was collected immediately before cover crop termination (Table 2) from a 0.5 m^2 sampling area, 0.3 m away from plot borders. To maximize flowering time yet avoid seed-set and cover crops reseeding, cover crops with early [buckwheat (Fagopyrum esculentum Moench)] and medium-length [phacelia monoculture (*Phacelia tanacetifolia* Bendth), and oat (*Avena sativa* L.), field pea (*Pisum sativum* subsp. *Arvense* L.), and clover (*Trifolium incarnatum* L., *T. alexandrinum* L., *T. pratense* L., *T. repens* L., *T. hybridum* L.) mix] flowering were terminated on July 15, sunn hemp (*Crotalaria juncea* L.) was terminated July 29 due to low biomass production and no flowering, and late-flowering crops [sunflower (*Helianthus annuus* L.)] were terminated on Aug 13. Aboveground biomass samples were categorized and sorted as cover crops and weeds, then oven-dried at 60 °C for at least 48 hrs. Samples were then weighed, and ground to 2mm for C:N ratio determination. One sunn hemp treatment plot had no biomass collected due to low germination; this plot was excluded from analysis. Cover crop termination was performed with a walk-behind tractor (BCS) and flail mower attachment. Due to unfavorable weather conditions and wet soils, biomass could not be incorporated in the soil with rotary tillage until two weeks after termination. Soils were sampled at cover crop termination and again approximately two weeks following tillage (Table 2). Ten soil cores were collected to 15 cm depth, using 2.5 cm diameter stainless steel soil probes, and homogenized. Samples were stored in paper bags and oven-dried at 35 °C for at least 48 hrs. Dry soil samples were ground to 2 mm for soil inorganic N (NO_3^--N) analysis. Inorganic NO_3^--N was measured using a KCl extraction (modified from

Robertson et al. 1999). Briefly, 8 g of dry soil was weighed into 50 mL centrifuge tubes, 40 mL 1 M KCl was added, and tubes were shaken for 1 h at approximately 240 rpm. Samples were allowed to settle for at least 1 h, and supernatant was filtered through #1 Whatman papers and collected in scintillation vials. Vials were frozen for analysis, which was later performed using a colorimetric nitrate assay (Doane and Horwarth, 2003). Biomass was analyzed for C and N content using a dry combustion analyzer (Elementar VarioMax CN analyzer).

Floral and Arthropod Sampling

Flower units was the measurement used to quantify flower abundance. Each individual species was quantified and recorded within a 0.5 m^2 area, beginning when ten or more open flower units were observed within each plot (Table 2). Flower units were categorized depending on the species. For buckwheat and phacelia, each bifurcated stem was considered one flower unit. Flower units for sunflower, clovers and field peas were determined by each inflorescence. Cover crop peak blooms were categorized as early, early-mid and late bloom time (Fig. 2). Plots were terminated when buckwheat started producing mature seeds (i.e., dark colored-filled pods), even if other species from the treatment were not in bloom (Table 2). Beneficial arthropod communities were sampled every 7-8 days by sampling the perimeter of each plot with a sweep net for 60 seconds. Sampling did not occur the week of July 7-17 due to weather conditions. After collection, arthropods were preserved in a -20 °C freezer until family level taxonomic identification, and preserved in an 80% ethanol solution thereafter. Specimens were identified to family

using the keys provided by Triplehorn et al. (2005) and Marshall (2006) as well as photographs and descriptions available in www.BugGuide.net. Selected specimen identifications were verified by Dr. Ralph Holzenthal, Department of Entomology, University of Minnesota. Beneficial arthropod abundance, diversity, and richness were assessed and categorized by functional groups for all flowering cover crops. Voucher specimens were deposited in the University of Minnesota Insect Collection, St. Paul.

Statistical Analysis

For soil and cover crop biomass, we report dry biomass quantity (kg ha^{-1}), biomass N content (kg N ha^{-1}), and soil N (NO_3^--N) at 0 and 2 weeks after biomass incorporation. Changes reported in NO_3^--N were calculated by subtracting mean pre-termination soil NO_3^--N values from those taken two weeks following termination. Because soil conditions (temperature and moisture) are known to impact N mineralization rates, and times of sampling and termination in this study varied by flowering times (Table 2), reported soil NO_3^--N values should be considered as a potential of summer cover crops, and not absolute. Cover crop treatment fixed effects on soil properties and biomass production ($P < 0.05$) were analyzed using a mixed effects model ANOVA with replication as a random effect (package lme4; Bates et al., 2015). Floral, beneficial arthropod and predominant group taxa abundance as a function of cover crop treatments were analyzed using a generalized linear model with a Poisson family distribution (package R; R Core Team, 2019). Beneficial arthropod data is reported as total number and relative abundances of collected families by treatment. To assess diversity of

pollinators and natural enemies, for each experimental unit Shannon indices were calculated using insect family as a proxy for species (R vegan package; Okansen et al., 2019). Linear mixed effects models with terms for cover crop treatment as the main effect and replicated plot as a random effect were used to compare richness and diversity of natural enemies among treatments (package lme4; Bates et al., 2015). Response variables of biomass, biomass N, richness and Shannon's diversity indices were square root transformed to normalize error and satisfy the assumption of equal variance. All analyses were conducted with R, version 3.5.3 (R Core Team, 2019) and RStudio, version 1.2.1 (RStudio Team, 2018).

RESULTS & DISCUSSION

Biomass Production, C:N Ratio, and Soil Inorganic N

Cover crop biomass production (kg ha^{-1}) varied across treatments ($P < 0.001$) with higher-biomass treatments trending towards higher N-contributing treatments. The oat, field pea and clover (OFC) treatment produced the greatest biomass (8747 ± 1600 kg ha^{-1}) and suppressed the most weeds (Table 3). This treatment also produced the highest biomass N (265 ± 73 N kg ha^{-1}), attributed to its high biomass and low C:N ratio. Clover biomass did not reflect the original proportion of clover in the OFC mix, resulting in an over-representation of oats and field peas in this treatment. Although many clovers are slower to establish than either field pea or oat, and often do not flower the first year, crimson clover flowered by week three. As expected, weed biomass was

negatively correlated to cover crop biomass ($P < 0.001$, $R^2 = -0.63$). This result supports previous findings that summer-planted cover crops can produce sufficient biomass to be competitive with weed species (Finney et al., 2016; Sharma et al., 2018; Stepanovic et al., 2018). Sunn hemp, a buckwheat and partridge pea mix (BP), and the most diverse plant family mix (MD) had low cover crop biomass and correspondingly greater amounts of weeds due to poor germination relative to other treatments. Sunn hemp is a warm-climate cover crop that is extensively used in the southern US and the Caribbean (Morris et al., 2015; Halbrent, 2010). Sunn hemp germination may have been affected by cooler air and soil temperatures during the planting dates of May 1 and May 15, when temperatures in Minnesota varied between 7 and 25 °C. The mixture treatments, BP and MD, both included buckwheat, known to have rapid establishment and competitive germination, potentially affecting establishment of other species in the mix. However, the mix containing buckwheat, annual ryegrass and clovers (BAC), had comparable biomass to phacelia and sunflower, second and third highest biomass production species. Clover species' germination in BAC were not representative of seeding rate.

Soil NO_3^--N varied across treatments ($P < 0.001$), increasing from 26 to 55% two weeks following biomass incorporation in BP, BPhS, and OFC treatments (Figure 1). Although this is expected for OFC, which produced significantly higher biomass N that likely drove the soil N increases, this result was surprising for BPhS and BP, as these treatments did not produce substantially greater amounts of biomass N relative to any other treatment. In these cases, available soil N could possibly have increased via N inputs not

quantified in this study, including N from root residue decomposition (Bukovsky-Reyes et al., 2019).

Cover crop mixtures that include legumes or other low C:N biomass species often increase soil health indicators, including soil organic matter and N (Finney et al., 2016; Kaye et al., 2019). We observed 73 to 100% greater biomass N provided by the OFC treatment relative to all other treatments. However, other treatments that also included legumes with non-legume components (Table 1) did not produce comparable amounts of biomass N. These other treatments included buckwheat, known to have earlier and faster growth rates (Hogg et al., 2011) relative to other species included in the evaluated mixtures. This rapid growth of buckwheat may have decreased legume productivity and subsequent N contributions via competitive effects. Legumes generally contribute higher biomass N than buckwheat, with recorded levels of 217 kg ha^{-1} N compared to 21.3 kg ha^{-1} , respectively (Marcinkonis et al., 2007; Parr et al. 2011), yet individual species' productivity in a given environment ultimately controls overall N contributions. Among the buckwheat-containing treatments, the BAC mix trended towards higher biomass N, but was not statistically different from B, BP, MD treatments ($P > 0.05$). The MD treatment had 51 to 79% lower biomass production compared to OFC and BAC mixes, and to phacelia and sunflower monocultures, also likely attributed to competition with mixture components (Sarrantonio, 2007). Results support that selecting appropriate competitive plant traits for mixes, especially favoring legumes, may present a challenge, as greater competitive establishment may benefit weed control but decrease germination of other mix species.

Floral Resources

Buckwheat treatments started flowering extensively 42 d after planting date. Sole crop buckwheat produced the highest mean floral peak (flower units = 374 ± 95.9) relative to other treatments containing buckwheat (ranging from 56.2 ± 14.1 to 202 ± 71.6). Phacelia began flowering progressively 42 d after planting date, reaching peak bloom by July 9th (181 ± 53.4), and culminating July 30th. Although both buckwheat and phacelia monocultures had started flowering by the first collection sample, buckwheat in mixed culture flowered 14 days earlier than phacelia, providing early floral resources for a wide range of arthropod visitors. The OFC treatment started flowering 42 d after planting date and reached an average peak bloom of 11.2 ± 2.9 flower units. The sunflower treatment had a period of 76 d to flower from planting date, lasting 14 d and with an average peak bloom of 8.9 ± 1.6 flower units. The sunn hemp treatment did not provide flowers during the experimental period.

Beneficial Arthropod Abundance, Diversity, and Richness

Across all treatments a total of 2,668 arthropod specimens were collected from cover crop treatments, of which 25% (667) were categorized as beneficial arthropods (Hill, 1997), including natural enemies (predators and parasitoids) and pollinators (bees and hoverflies). Specimens that were not considered to be beneficial arthropods were either categorized as agricultural pest, including aphids (Family: Aphididae) and thrips (Family: Thripidae), or neutral, such as ants (Family: Formicidae) and butterflies (Order: Lepidoptera). The 667 beneficial specimens were subset into 18 taxonomic families with

Syrphidae (68.1% of individuals) and Apidae (7.3%) comprising more than 75% of all specimens collected, followed by Coccinellidae (5.5%) and Eulophidae (4.5%). Syrphidae had the highest relative abundance (77.9%), followed by Coccinellidae (21.8%) and Apidae (16.2%) (Table 4).

Abundance of beneficial arthropods in the OFC and sunflower treatments were lower than all other treatments, likely attributed to low inflorescence production in both treatments. The MD treatment had the highest abundance of total beneficial arthropods (147) relative to both OFC (53) and S (28) treatments (Table 4). However, this was not statistically different from buckwheat, BAC, BP, BPhS, and phacelia treatments.

Plant functional diversity has been correlated with higher arthropod diversity in a perennial savannah grassland (Haddad et al., 2001). However, our results demonstrate that higher plant functional diversity does not necessarily result in higher arthropod diversity. Although the MD treatment had the greatest beneficial arthropod abundance, it had lower richness than the monoculture or bi-culture treatments. Buckwheat (diversity / richness, respectively; 0.66 ± 0.14 / 2.6 ± 0.26) and BP (0.67 ± 0.17 / 2.6 ± 0.42) treatments had a higher richness than the MD (0.22 ± 0.08 / 1.3 ± 0.28) and phacelia (0.26 ± 0.10 / 1.5 ± 0.29) treatment. B, BAC, and BP displayed higher richness but no significant difference in diversity relative to OFC (0.35 ± 0.11 / 1.4 ± 0.29) treatment. BAC (0.68 ± 0.20 / 3.0 ± 0.60) treatment showed difference in diversity compared to sunflower (0.37 ± 0.12 / 1.9 ± 0.19), however no difference in richness.

Members of the family Syrphidae are known to be attracted to small, white flowers such

as buckwheat, *Lobularia* (alyssum) spp. and *Coriandrum sativum* (Hogg et al., 2011; Martinez-Uña et al., 2014). Considering these specimens composed 68% of the total amount of beneficial arthropods collected, the higher amounts of beneficial arthropods in treatments containing buckwheat (Table 4) is consistent to previous studies and throughout our treatments. Additionally, Phacelia sp. was particularly attractive to native and non-native pollinator groups such as *Bombus,* Halictidae, and honeybees (*Apis mellifera*) (Table 4). The sunflower treatment flowered the latest and had short flowering length, explaining the low abundance of arthropods captured. However, arthropod diversity in sunflower was equivalent to longer-flowering treatments, demonstrating the capacity of sunflowers to attract a wide range of beneficial arthropods even during a shorter flowering period. Native species are believed to have co-evolved with endemic natural enemies (James et al., 2014). Therefore, sunflowers, which are native to North America, may play a key role in attracting and sustaining endemic beneficial arthropod populations (Fiedler et al., 2007).

CONCLUSIONS

This research explored the effect of summer-planted flowering cover crop mixes on concurrent N provision and presence of floral resources for beneficial arthropods. Nine treatments containing one to seven species of cover crops were evaluated for flowering time, N content, soil N contribution, and beneficial arthropod attraction. The oat, field

pea, and clover mix added the most biomass, followed by phacelia and sunflower monocultures. The OFC treatment also provided the greatest increase in soil NO_3^--N from 0-2 weeks after biomass incorporation relative to all other treatments. Buckwheat monoculture and mixes demonstrated the shortest time to flower and ranked higher in all three arthropod indices: abundance, diversity and richness. In the Upper Midwest, a short summer fallow period in organic vegetable crop rotations presents a valuable opportunity to introduce cover crop mixes and provide additional ecosystem services. Such mixes typically include a variety of grasses, legumes and brassicas. Expanding cover crop options to include non-traditional flowering species attractive to beneficial insects, such a phacelia, may increase the provision of desired ecosystem services. As these flowering cover crop mixtures are introduced into farmer's rotations, pollinator presence may also be increased. More research is needed to determine optimal termination timing, given that longer growth is needed for flowering, but the physiological changes associated with flowering could lead to less biomass-N availability (Schiltz et al., 2005). This trade-off between ecosystem services is especially challenging to manage when using cover crop mixes. A mix with varying bloom times can extend the degree of pollinator habitat provision, yet leads to inconsistent biomass quality among mix species, as well as potential termination time challenges, as some species may go to seed prior to other species. Further research of ecosystem services trade-offs such as this is required to obtain greater clarity of their interactions and to what extent summer-planted cover crops may supply multifunctionality.

TABLES AND FIGURES

Table 1. Treatment acronyms divided by species' common and scientific name (in parenthesis) and separated by commas. Seeding rates shown by order of treatment species appearance in common (scientific) name column and separated by commas. Asterisks indicate equal seeding rate for all clover species in a mixture.

Treatment	**Common (scientific) name**	**Seeding rate ($kg \cdot ha^{-1}$)**
B	buckwheat (*Fagopyrum esculentum* Moench)	113
Ph	phacelia (*Phacelia tanacetifolia* Bendth.)	14
S	sunflower (*Helianthus annuus* L.)	11
Sh	sunnhemp (*Crotalaria juncea* L.)	23
BAC	buckwheat, annual ryegrass (*Lolium multiflorum* L.), and clover spp. (crimson clover (*Trifolium incarnatum* L.), berseem clover (*T. alexandrinum* L.), medium red clover (*T. pratense* L.), ladino white clover (*T. repens* L.), and alsike clover (*T. hybridum* L.)	23, 23, 2*
BP	buckwheat and partridge pea (*Chamaecrista fasciculata* Michx.)	79, 17
BPhS	buckwheat, phacelia, and peredovik sunflower	19, 3, 2
MD	buckwheat, canola (*Brassica napus* L.), oilseed radish (*Raphanus sativus* L.), field peas, pearl millet (*Pennisetum glaucum* L.), and oats	8, 1, 1, 17, 3, 11
OFC	oats (*Avena sativa* L.), field peas (*Pisum sativum* subsp. *Arvense* L.), and clover spp.	113, 113, 2*

*Consistent for all clover species

Table 2. Dates of field operation with day and month separated by a hyphen. Multiple dates on the same month (separated by a comma) and on different months (separated by a semi colon) within a cell indicate repetition of the operation.

	Date
Operation	**2018**
Early cover crop planting	1-May
Late cover crop planting	15-May
Flower counts	26-Jun; 3, 9, 16, 23, 30-Jul; 6-Aug
Insect counts	26-Jun; 9, 11, 16, 23, 30-Jul; 3, 6 Aug
Sampled biomass	15, 29-Jul; 13-Aug
Mowed cover crops	15, 29-Jul; 13-Aug
Sampled soil (post-mowed)	15, 29-Jul; 13-Aug
Tilled biomass	31-Jul; 19, 29-Aug
Sampled soil post-tillage	14-Aug; 3, 10-Sep

Table 3. Mean C:N ratio, aboveground biomass (kg N ha^{-1}), aboveground biomass N (kg N ha^{-1}) and percent N (%) in cover crop and weed populations by treatment acronyms. Soil inorganic NO_3-N (ppm) displayed before biomass tillage (at biomass termination) and two weeks after biomass tillage to shown differences in soil nitrate-N levels after cover crop integration. Results followed by the same letter within each column are not different ($P < 0.05$). Acronyms defined by species' common names in table footnote.

	Cover crop						**Weed**		
Cover Crop Treatment	**C:N**	**biomass**	**biomass N**		**soil inorganic NO_3-N**		**C:N**	**biomass**	**biomass N**
		kg N ha^{-1}	**%**	**kg N ha^{-1}**	**before**	**after**		**kg N ha^{-1}**	**kg N ha^{-1}**
B	31.1 bc	2730 cd	1.5	43.1 bc	1.3 b	8.1 b	25.1 b	2295 b	39.0 bc
BAC	24.8 c	3847 bc	1.8	70.4 b	1.3 b	7.5 bc	29.8 b	1330 bc	19.5 c
BP	37.3 ab	1955 d	1.2	23.7 bc	1.3 b	10.6 ab	25.7 b	2025 b	34.1 bc
BPhS	31.8 b	2386 cd	1.3	31.1 c	1.3 b	11.1 a	26 b	2115 bc	35.6 bc
MD	17.3 d	1866 d	2.8	53.5 bc	1.6 ab	8.2 b	25.9 b	2600 b	45.3 b
OFC	16.0 d	8747 a	2.9	265.6 a	2.5 a	13.5 a	18.3 c	377 c	8.7 c
Ph	34.3 b	5035 b	1.2	61.7 bc	1.2 b	7.5 bc	23.7 bc	691.5 c	12.1 c
S	42.3 a	4250 bc	1.1	46.9 bc	0.5 c	5.5 c	41.2 a	3760 ab	44.4 bc
Sh	20.9 cd	20 e	2.2	0.6 d	1.2 b	6.1 bc	30.2 b	5735 a	84.3 a

B: buckwheat; BAC: buckwheat, annual ryegrass, and clovers; BP: buckwheat and partridge pea; BPhS: buckwheat, Phacelia and sunflower; MD: buckwheat, canola, radish, field peas, pearl millet, and oats; OFC: oats, field peas, and clovers; Ph: Phacelia; S: sunflower

Table 4. Season-long total number of individuals and relative abundance (RA) for each taxon encountered across nine treatments. B: buckwheat; BAC: buckwheat, annual ryegrass, and clovers; BP: buckwheat and partridge pea; BPhS: buckwheat, Phacelia and sunflower; MD: buckwheat, canola, radish, field peas, pearl millet, and oats. Taxa categorized by alphabetical order and family (indent) level. Dash lines indicate that the family specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

Taxa	**B**		**BAC**		**BP**		**BPhS**	
	Total	**RA(%)**	**Total**	**RA(%)**	**Total**	**RA(%)**	**Total**	**RA(%)**
Coleoptera								
Coccinellidae	--	--	3	3.2	--	--	2	3.4
Diptera								
Syrphidae	67	76.1	74	77.9	46	67.6	41	69.5
Hemiptera								
Anthocoridae	2	2.3	1	1.1	1	1.5	--	--
Reduviidae	2	2.3	--	--	--	--	--	--
Hymenoptera								
Andrenidae	--	--	--	--	--	--	--	--
Anthophorini	--	--	--	--	--	--	--	--
Apidae	3	3.4	1	1.1	11	16.2	7	11.9
Braconidae	2	2.3	1	1.1	2	2.9	--	--
Colletidae	--	--	--	--	--	--	1	1.7
Encyrtidae	--	--	1	1.1	--	--	--	--
Eulophidae	5	5.7	5	5.3	4	5.9	2	3.4
Eurytomidae	--	--	1	1.1	--	--	1	1.7
Halictidae	1	1.1	2	2.1	--	--	2	3.4
Ichneumonidae	--	--	--	--	--	--	--	--
Pteromalidae	3	3.4	--	--	2	2.9	2	3.4
Sphecidae	--	--	1	1.1	--	--	--	--
Vespidae	--	--	--	--	--	--	--	--
Neuroptera								
Chrysopidae	3	3.4	5	5.3	1	1.5	1	1.7
Odonata								
Coenagrionidae	--	--	--	--	1	1.5	--	--
Total	88		95		68		59	

Table 4. Season-long total number of individuals and relative abundance (RA) for each taxon encountered across nine treatments. B: buckwheat; BAC: buckwheat, annual ryegrass, and clovers; BP: buckwheat and partridge pea; BPhS: buckwheat, Phacelia and sunflower; MD: buckwheat, canola, radish, field peas, pearl millet, and oats. Taxa categorized by alphabetical order and family (indent) level. Dash lines indicate that the family specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Total numbers on the far right indicate summed values of a family specific to that row.

Taxa	**MD**		**OFC**		**Ph**		**S**		
	Total	**RA(%)**	**Total**	**RA(%)**	**Total**	**RA(%)**	**Total**	**RA(%)**	**Total**
Coleoptera									
Coccinellidae	32	21.8	--	--	--	--	--	--	37
Diptera									
Syrphidae	97	66.0	31	58.5	96	72.7	2	7.1	454
Hemiptera									
Anthocoridae	--	--	1	1.9	1	0.8	2	7.1	8
Reduviidae	--	--	--	--	--	--	--	--	2
Hymenoptera									
Andrenidae	--	--	2	3.8	--	--	1	3.6	3
Anthophorini	--	--	--	--	--	--	5	17.9	5
Apidae	2	1.4	1	1.9	20	15.2	4	14.3	49
Braconidae	3	2.0	7	13.2	1	0.8	2	7.1	18
Colletidae	1	0.7	--	--	--	--	--	--	2
Encyrtidae	1	0.7	--	--	--	--	1	3.6	3
Eulophidae	7	4.8	4	7.5	1	0.8	2	7.1	30
Eurytomidae	1	0.7	--	--	--	--	--	--	3
Halictidae	--	--	--	--	12	9.1	1	3.6	18
Ichneumonidae	1	0.7	2	3.8	--	--	--	--	3
Pteromalidae	2	1.4	4	7.5	--	--	8	28.6	21
Sphecidae	--	--	--	--	--	--	--	--	1
Vespidae	--	--	1	1.9	--	--	--	--	1
Neuroptera									
Chrysopidae	--	--	--	--	1	0.8	--	--	11
Odonata									
Coenagrionidae	--	--	--	--	--	--	--	--	1
Total	147		53		132		28		670

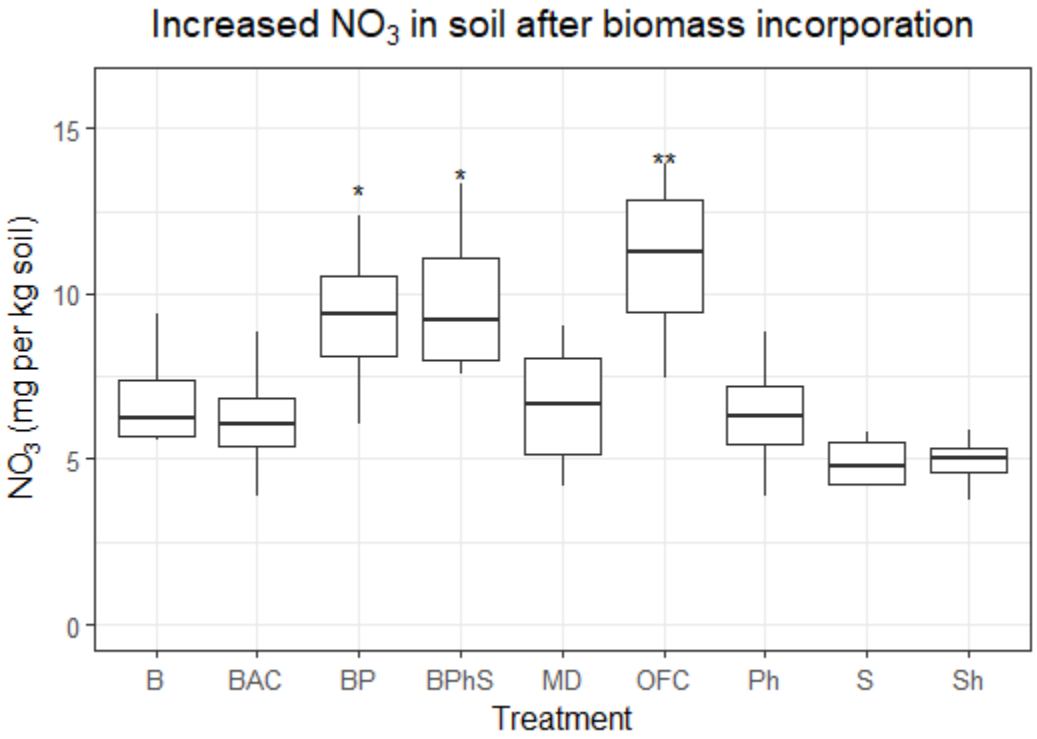

Figure 1. Effect of cover crop treatments on inorganic nitrate-N (NO_3–N in mg per kg of soil) from zero to two weeks after biomass incorporation. B (buckwheat), BAC (buckwheat, annual ryegrass and clovers), BP (buckwheat and partridge pea), BPhS (buckwheat, Phacelia and sunflower), Most diverse (MD) (buckwheat, canola, radish, field peas, pearl millet and oats), OFC (oats, field peas and clovers), Ph (Phacelia), S (sunflower) and Sh (sunnhemp). Asterisk over boxes denote statistically different means at $P \leq 0.05$ (*) and $P \leq 0.001$ (**).

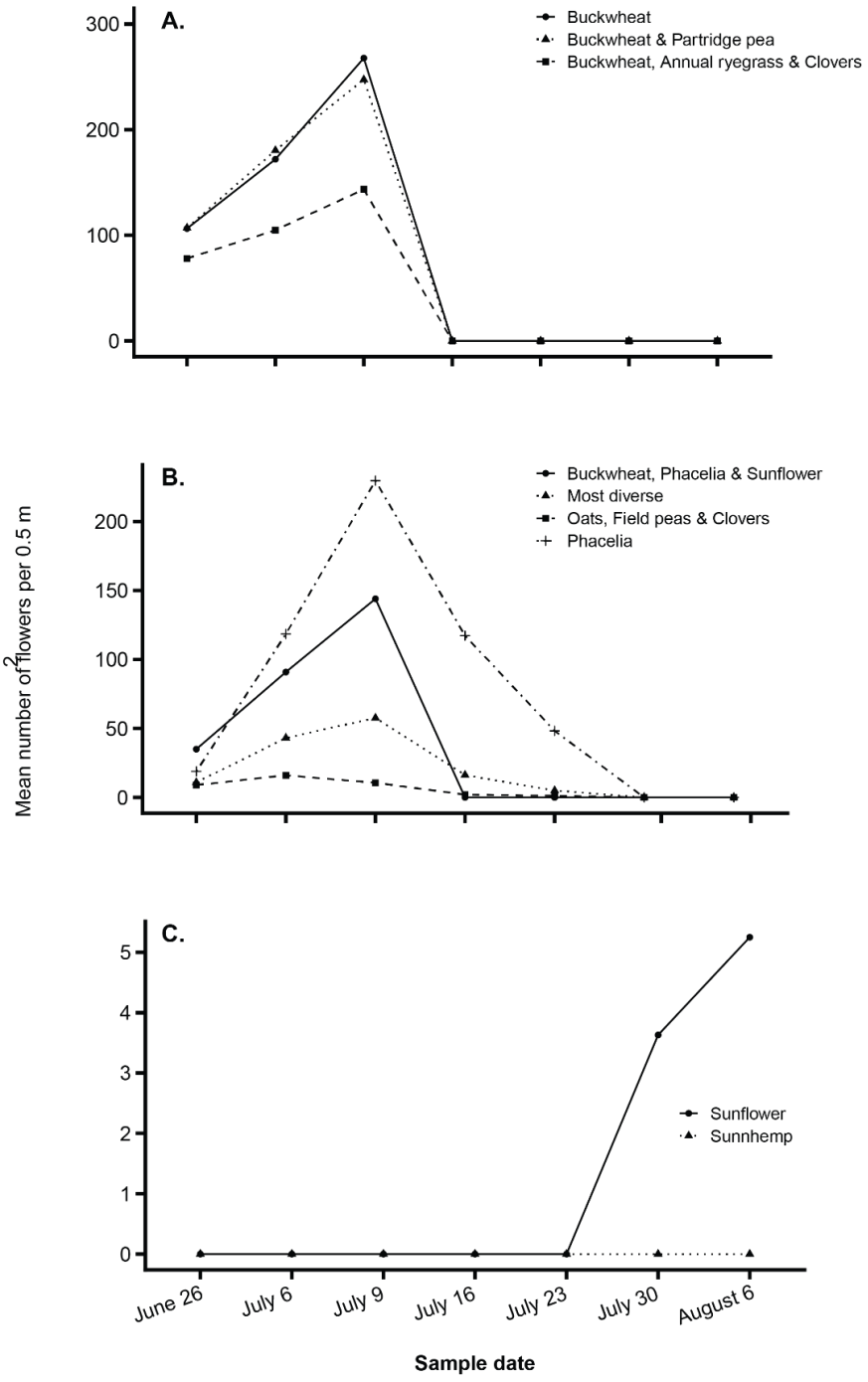

Figure 2. Mean numbers of open flowers per 0.5 m^2 across time from June 26th to August 6th. Treatment plants separated in figures by flowering period at (A) early, (B) mid-early, and (C) late flowering. Treatment groups indicated by geometric figures and pattern or solid lines.

CHAPTER 3 – MAXIMIZING ARTHROPOD CONSERVATION WITH SUMMER COVER CROPS IN ORGANIC VEGETABLE SYSTEMS

SUMMARY

Many vegetable crop rotations leave little time or space to integrate beneficial arthropods and pollinator habitat; the lack of habitat causes population declines, which can lead to insufficient pollination services and increased pest incidence. In Minnesota, two rotation systems present a valuable opportunity to introduce summer cover crop species that provide key multifunctional ecosystem benefits to vegetable crop production. The first system is an early summer-planted cover crop followed by a broccoli cash crop, and the second system consists of an early spring lettuce planting followed by a late-summer-planted cover crop. As these flowering cover crops are introduced into rotations on-farm, pollinator presence may also be increased by providing a continuity of resources, conserving beneficial species for longer periods. This research focuses on evaluating the ability of flowering summer cover crops to attract beneficial arthropods by measuring abundance, richness, evenness, and overall diversity of arthropod communities in three regions of Minnesota. These measurements were carried out by collecting arthropod data, through observational and vacuum sampling, and flower counts, to determine abundance and phenology of attractive floral cover crops. Results show differences in cover crop treatments and family, genus or species abundance by early and late cover crop planting systems. In both years, planting systems affected flower phenology with greater production of flowers in the early versus the late planting, except for sunflower. These results demonstrate the capacity of cover crops to expand the seasonal availability of floral resources in agroecosystems.

INTRODUCTION

Natural vegetation affected by land management has a substantial influence on wild pollinators and beneficial arthropods, which are dependent on their surrounding environments in order to acquire forage and nesting spaces. (Kaplan *et. al*, 2010; O'Conner, 2013). The clearing of land for agriculture is a main driver of biodiversity loss, which directly detracts from landscape multifunctionality by decreasing insect habitat and alternate insect host species availability (Pulleman et al., 2000; Tilman et al., 2002). Intensive vegetable systems that do not integrate diversified floral resource have contributed to declines in natural and semi-natural habitats. Although agricultural systems may likely never replicate complex and robust multifunctional natural ecosystems, by adding more intentional species with diverse functions, we can move closer to the multifunctional landscapes of natural environments.

Due to high specificity in arthropod food source selection, it is critical to include diverse floral resources throughout the year (O'Conner, 2013). Constant forage availability from early spring to late summer is particularly imperative for the survival of social insects with long-lived colonies, such as bees (Carreck and Williams, 2001). Flower pollen and nectar provide a significant amount of nutrition for pollinators, parasitoids and predators, especially when prey is scarce (Landis et al., 2005; Wäckers et al., 2005). The use of cover crops can expand the seasonal availability of floral resources in agroecosystems

(Hooks et al. 1998; Landis et al. 2005). Cover crops are non-food crops that provide ecosystem services, such as N provision, organic matter, provide floral resources and thus may promote beneficial insect floral visitation, among many others (Reicosky and Forcella, 1998; Fageria et al., 2005; Campbell et al., 2006; Blanco et al., 2015; Bulan et al., 2015; Sharma et al., 2018). Cover crops can be integrated in many divergent cropping systems, including temporally, before or after a cash crop, or spatially, as an intercrop between cash crops, or in fallow areas (Creamer and Baldwin, 2000; Finney & Kaye, 2017; Blesh et al., 2019). Planting summer cover crops to diversify agroecosystems can positively impact beneficial arthropod populations, such as increased diversity and abundance of wild bees and other pollinators (Wilson et al., 2018; Hecht, 2019).

Different flower species receive diverse arthropod visitation. Flowers have become more specialized and arthropods more selective of floral resources through coevolution (Nicholls & Altieri, 2013). Research has positively correlated bee species abundance in a given landscape with plant species diversity and flowering vegetation areas relative to bare plots (Banaszak, 1996). Buckwheat (*Fagopyrum esculentum* Moench), a commonly used cover crop throughout the US, increased female and male wasp lifespan by at least two-fold, relative to wasps supplied with water only (Nafziger and Fadamiro, 2011). Besides direct contributions to beneficial arthropods, including pollen and nectar, cover crops provide indirect benefits by supporting alternate hosts and moderating microclimate (Landis et al., 2005). Aside from being a preferred host plant for many wasps and bees (Carreck and Williams, 2001; Hogg et al., 2011), borders of phacelia explored in cabbage

fields increased presence of syrphid flies, while aphid populations declined (Landis et al., 2000).

Regardless of the advantages provided by cover crops, in 2017, only 7.5% of farmers in the US had integrated cover crops in some parts of the farm; whereas in the US Corn Belt (Indiana, Illinois, Iowa, and Minnesota), around 37% of farmers had used cover crops in their farming system (USDA, 2017). Understanding how ecologically imperative these conservation efforts may be, and their current limited adoption in agroecosystems of the Upper Midwest, we researched the viability of summer cover crops in organic rotation systems to address knowledge gaps of how specific floral cover crop species may behave in the US northern-central region. We formulated three objectives to accomplish our goal: (1) evaluate phenology of cover crop species in early and late summer planting times to identify flowering period and establishment viability, (2) assess capacity of summer flowering cover crops to increase beneficial arthropod density relative to a weedy-fallow, and (3) determine dominant arthropod groups in early and late summer planting times to identify principle functionalities, diversity, richness, and evenness of groups.

MATERIALS AND METHODS

Experimental Location and Treatments

Summer-planted cover crop trials were established twice in the growing season, from May to July and from July to October in 2020 and 2021. Research plots were located at three locations in Minnesota, including (1) the University of Minnesota Agricultural Experimental Station (MAES) - Twin Cities campus, St. Paul (StP) (44.990829, -93.175832), (2) Big River Farms (BRF), Marine on St. Croix (45.168877, -92.815290), and (3) at White Earth Nation (WE), Mahnomen (47.325903, -95.958302). Cover crop species were selected to represent commonly used Upper Midwest cover crops, expected beneficial arthropod floral preference, and predicted soil nutrient contributions based on past trials. Results from an on-farm preliminary trial in 2019 (Candelaria et al., 2022), recommendations from the Xerces Society for Invertebrate Conservation, and farmer collaborator preferences further supported species selection (Table 1). In St. Paul, regional mean annual rainfall is 813 mm, and the soil is classified as a Crystal Lake silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls). In BRF regional mean annual rainfall is 838 mm, and the soil is classified as a Crystal Lake silt loam (fine-silty, mixed, superactive, frigid Oxyaquic Glossudalfs). In WE regional mean annual rainfall is 521 mm, and the soil is classified as a Hamerly-Vallers complex (fine-loamy, mixed, superactive, frigid Aeric Calciaquolls). In 2020, due to Coronavirus Disease-2019 (COVID-19) restrictions, the study was only performed in StP and BRF. Treatments were arranged in a randomized complete block experimental design with four replications. Treatment plot size was 3 m^2 in StP, 3.6 m x 2.3 m in BRF, and 2.7 m x 2.4 m in WE. Weed-free strips were established within plot boundaries to maximize flower production and prevent vacuum sampling of arthropod specimens

visiting weed flowers. Weed-free strips were weeded by hand biweekly and strips measured 3 m x 1 m in StP, 2.3 m x 1 m in BRF, and 2.4 m x 1 m in WE. Cover crops were broadcast sown at two summer dates - early (May) and late (July) -, lightly raked to increase seed to soil contact, and terminated through mowing at the time of seed formation (Table 2). Early-planted cover crops were terminated in July and followed by fall broccoli (*Brassica oleracea* var. italica), whereas late-planted cover crops followed lettuce (*Lactuca sativa*) planting and were left to winterkill. Due to severe drought in 2021, four out of six cover crop treatments were reseeded in the late planting in BRF, including phacelia (*Phacelia tanacetifolia* Bendth.) and crimson clover (*Trifolium incarnatum* L.) monocultures, and sunflower (*Helianthus annuus* L.) and oat (*Avena sativa* L.), and field pea (*Pisum sativum* subsp. *Arvense* L.) and oat bicultures. In the early planting, all cover crops were terminated when buckwheat started producing mature seeds (i.e. dark colored-filled pods), and within sufficient time to rotate in the vegetable crop (Table 2). In the late planting, cover crops were left to winterkill, which extended flowering time. However, reseeded cover crops in BRF did not bloom in time to collect flowering and arthropod data, except for field pea. Previous fertility management in StP prior to experiment establishment included historical manure additions, as well as buckwheat sown in 2019. No synthetic or organic fertilizers and pesticides were applied in the two years prior to the experiment, or during the experimental growing season. *Apis mellifera* density in StP is correlated with maintained beehive number, making them abundant, as the field site was in proximity to a bee laboratory. Fertility management in BRF consisted of Sustane 8-2-4 (Sustane Natural Fertilizer, Inc., Cannon Falls, MN) and

Drammatic K (Dramm Corporation, Manitowoc, WI) in both years of experimental seasons, while in previous years received compost application, mixed vegetables and diverse cover crop species establishments. In WE, pelletized chicken manure was applied, based on soil test recommendations, once at the end of May during the experimental growing season to increase cover crop establishment likelihood, as soils had substantially lower than average soil fertility for the Midwest. Additionally, arthropod identification in WE was performed at a higher taxonomic category, i.e. morphospecies, which may have skewed data results.

Floral and Arthropod Sampling

We defined floral unit as the collected data unit used to quantify floral abundance. Each individual species was quantified and recorded within a 0.5 m^2 area inside the weed-free strips, with data collection beginning when ten or more open floral units were observed within each plot (Table 2). Floral units were categorized depending on the species' floral morphology. For buckwheat (*Fagopyrum esculentum* Moench) and phacelia, each bifurcated stem was considered one floral unit. Floral units for sunflower, clovers and field peas were determined by each compound inflorescence or capitulum, rounded cluster, and distinct raceme bloom, respectively. Cover crop species were categorized as either early, mid, and late flowering species (Fig. 1 and 2). Both flower and arthropod communities were sampled in each location every 6 to 8 days, depending on weather conditions. Optimal weather conditions and sampling hours were sought to be sunny,

clear skies with temperatures ranging from 18 and 29 °C, between 9:00 am and 2:00 pm. Arthropod sampling was performed via two methods, vacuum collections and observational surveys, in order to explore collection potentials for both methods. Vacuum sampling was only carried out in StP, whereas observational surveying was performed in all three locations. Vacuum sweeps were carried out within the area of each weed-free strip for 60 seconds, using a Heavy-Duty Hand-Held DC Vacuum from BioQuip. Observational surveys were performed using the Xerces Society Upper Midwest citizen science monitoring guide and data sheets within the whole plot area, due to clear distinction of arthropod visitation to flowering cover crops relative to weed flower presence, for a total of 3 minutes. After vacuum collection, arthropods were preserved in a -20 °C freezer until specimens were identified to the lowest appropriate taxonomic level using the keys provided by Triplehorn et al. (2005) and Marshall (2006), as well as photographs and descriptions available in www.BugGuide.net. Selected specimens were pinned and labeled with location, collection date, collector information, and a unique identification code. Samples were organized phylogenetically after being verified by Dr. Ralph Holzenthal, Department of Entomology, University of Minnesota, and Jessica Miller, M.S., bee and environmental ecosystem specialist. Voucher specimens of selected taxa have been deposited in the University of Minnesota Insect Collection, Department of Entomology. Beneficial arthropod abundance, diversity, richness, and evenness were assessed and categorized by functional groups (i.e., pollinators, predators, and parasitoids) for all flowering cover crops (Hill, 1997).

Arthropod Observational Survey Training

For observational assessments, training on nine different bee groups and other flower visiting insects was provided by the Xerces Society for Invertebrate Conservation. In 2020, due to COVID-19, this workshop was only carried out once in Big River Farms and was limited to the first author, field assistant, and a BRF manager to accurately identify pollinators by observation. In 2021, the workshop was offered to farmers and community members in both BRF and WE. Participants took a presentation where different taxonomic traits of nine bee groups were discussed, including hairs, pollen storage morphological structures, size and shape, antennae, color, and stripes. These groups included: honey bees, bumble bees, chap leg, long-horned or digger bee (also known as *Melissodes*, Eucerini, or *Anthophora*), medium dark bees (which included both mining bees or *Andrena*, and plasterer bees or Colletidae), green sweat bee (or *Agapostemon* and *Augochlora*), stripped sweat bee (or *Halictus*), tiny dark bees (or *Lasioglossum*, *Hylaeus*, and *Ceratina*), stripped hairy belly bee (or Megachilidae), metallic hairy belly bees (or *Osmia*), and cuckoo bees (or *Sphecodes* and *Nomada*). After the presentation, participants visually sampled flowering cover crops in the field to identify insects based on bee groups and other flower visitors.

Statistical Analysis

Floral, beneficial arthropod, and predominant group taxa abundance as a function of cover crop treatment and planting time interaction were analyzed per location using a

generalized linear model with a Poisson family distribution if data was not over-dispersed, given count data use and non-normality assumption. A negative binomial generalized linear model was used when data was over-dispersed (package MASS; Venables and Ripley, 2002). Models were tested for homogeneity and significance ($P < 0.05$) was tested using a likelihood ratio test (chi square statistic). Beneficial arthropod data is reported as total number and relative abundances of collected taxa by treatment, planting time, and location (Table 3, 4, 5, 6, and 7). Low abundant or difficult to identify taxa were grouped into "Other" classifications. To assess diversity of beneficial arthropods in both methods, the number of individuals identified to their family taxonomy were summed over sample dates for each plot per location. Shannon's diversity indices were calculated using family taxonomy as proxy for species (R vegan package; Okansen et al., 2019). Linear models with terms for cover crop treatment and planting time interaction as fixed variable and diversity, richness, and evenness as response variables were used to compare arthropod population differences in planting times and among cover crop treatments and a weedy-fallow control (package stats; R Core Team, 2021). Linear models were tested through one-way ANOVAs (package stats; R Core Team, 2021). All analyses were conducted with R, version 4.1.2 (R Core Team, 2021) and RStudio, version 1.4.1 (RStudio Team, 2021). Results for StP and BRF are compared and displayed together, whereas WE was discussed separately, due to public participation in scientific research.

RESULTS & DISCUSSION

Floral Resources

At our southernmost site of StP, phacelia and crimson clover trended towards a greater floral peak in the early compared to the late planting, whereas buckwheat and field pea produced similar floral peaks between planting times in 2020 and 2021 (Figure 1a and 1b). For BRF in 2020 similar patterns were observed in the early planting, except for sunflower, where no floral production was observed among planting times (Figure 1a). In 2021 all treatments with exception to sunflower, which did not bloom in either planting, trended towards greater mean floral peaks in the early planting; however, late planting may have been substantially affected by drought conditions (Figure 1b). In our northernmost site of WE (Figure 1b), buckwheat and sunflower trended towards greater floral peaks in the late planting of 2021, while phacelia had a greater peak in the early planting. Other treatments showed no differences among planting times. Early cover crop planting in WE may have been potentially affected by low soil fertility and poor soil conditions at this site. Although pelletized chicken manure was added at the end of May, a few weeks after sowing early-planted cover crops, manure may not have decomposed at a parallel rate to flowering period. Additionally, the late planting of cover crops may have benefitted from greater soil conditioning following lettuce planting, as plant exudates have been observed to improve compression characteristics of soil (Oleghe et al., 2017). Averaged over both years by treatment, per location, buckwheat started flowering 34 d after planting in StP, 39 d in BRF, and 34 d in WE. Buckwheat has shown to have faster

blooming time than other species of cover crops, flowering 4 to 6 weeks after sowing (Cawoy et al., 2009). Phacelia flowered 60 d after planting in StP, 53 d in BRF, and 64 d in WE. Phacelia flowering phenology has been determined to be between 55-73 d after sowing, when sown in spring (Lermi and Palta, 2017), our results concur with these estimations. Crimson clover flowered 64 d after planting in both StP and BRF, field pea 54 d after planting in StP, 58 d in BRF, and 77 d in WE. Similar cover crop species flower phenology trends have been shown in previous studies. (Trevino and Murray, 1975; Sobrado and Turner, 1986; Chyzik et al., 1995; USA Pulses, 2009; Wilson, 2012; Candelaria et al., 2022). Blooming of late-planted sunflower occurred 64 days after planting in StP and at 77 d in WE. Early-planted cover crops were terminated between 59 to 62 days after planting, inhibiting floral development of early-planted sunflower. Sunflower did not bloom in BRF in either year regardless of planting time (Figure 1a and 1b). Similarly, crimson clover failed to bloom at WE in either year. Late-planted sunflower had poor germination in 2021 due to severe drought conditions and had to be reseeded at BRF.

Abundance, Diversity, Richness, and Evenness: Vacuum Collections

Averaged over reps, a total of 419 arthropod specimens were collected from cover crop treatments in 2020 and 1,442 in 2021, of which 40% (166) and 29% (413), respectively, were categorized as beneficial arthropods, including natural enemies (predators and parasitoids) and pollinators (bees and hoverflies), whilst the rest were either considered agricultural pest or functionally neutral. Beneficial specimens in 2020 were categorized

into 18 taxonomic families and one taxonomic class (Arachnida) (Table 3) with Syrphidae (14%) and Apidae (47%) comprising more than 60% of all specimens collected across all plant species and planting dates, followed by Anthocoridae (13%) and Halictidae (9%). Syrphidae had the highest relative abundance in early-planted buckwheat (53%) and oats and field pea (70%), Apidae in late-planted buckwheat (71%) and phacelia (74%), Anthocoridae in late-planted Sunflower and oats (41%), and Halictidae in early-planted phacelia (29%). Flower phenology and morphology including color, anatomy, and nectary structure, as well as nutrient content may influence beneficial arthropod preference of cover crop species (Vattala et al., 2006; Géneau et al., 2013). White, small flowers, such as buckwheat, have demonstrated to be preferred floral resources for members of the family Syrphidae (Hogg et al., 2011; Martinez-Uña et al., 2014). Abundant families were further identified to lower taxonomic levels. Apoidea families were subdivided into seven genera, including *Agapostemon*, *Apis*, *Bombus*, *Halictus*, *Lasioglossum*, *Melissodes*, and *Sphecodes* (Figure 2a). Since syrphid specimens have a simpler morphological taxonomy than Apoidea, most specimens were identified to species, including *Eristalis tenax*, *Eupeodes americanus*, *Platycheirus quadratus*, *Toxomerus marginatus*, and *Toxomerus geminatus* (Figure 3a). Due to some difficulty to identify *Sphaerophoria* spp., these were grouped at genus level, while other unclassified syrphid specimens were grouped as “Other Syrphidae”. *Orius insidiosus* was another abundant natural predator identified in our treatments, particularly late-planted sunflower and oats and sole phacelia (Figure 5a). Beneficial specimens in 2021 were subset into 25 taxonomic families and one taxonomic class (Arachnida) with greater presence from

Anthocoridae (43%), followed by Apidae (17%), Mymaridae (7%), and Halictidae (6%) across all plant species and planting dates. Anthocoridae had the highest relative abundance in late-planted buckwheat (55%), sunflower and oats (56%), and the weedy-fallow (69%), Mymaridae in late-planted field pea and oats (25%) and the early-planted weedy-fallow (36%), and Apoidea families Halictidae (54%) and Apidae (61%) in early- and late-planted phacelia, respectively (Table 4). *Phacelia tanacetifolia* has been classified among the twelve best plants for Apoidea species, possibly associated with greater nectar secretion levels, providing among the highest honey potentials ranging between 100 and 1,129 kg per hectare (Zimna, 1962, 1964; Baculinschi, 1964; Crane, 1975; Williams, 1997). Native species are believed to have co-evolved with endemic natural enemies and other arthropods (James et al., 2014). As a crop originally from North America, phacelia's nativity may be associated with greater native bee flower visitation (Carreck and Williams, 2001; Wilson et al., 2018). Similarly to 2020, abundant families were identified to lower taxonomic levels. Apoidea families were classified into five genera, including *Agapostemon*, *Apis*, *Bombus*, *Halictus*, and *Lasioglossum* (Figure 2b). Syrphids were further identified to species, including *Allograpta obliqua, Eupeodes americanus, Sphaerophoria contigua, Syritta pipiens, Toxomerus marginatus* (Figure 3b). Lady beetles were also identified to species due to a simpler morphological taxonomy, including *Coccinella septempunctata, Coleomegilla maculata, Harmonia axyridis, Hippodamia convergens*, *Hippodamia tredecimpunctata*, and *Hippodamia variegata* (Figure 4). *Orius insidiosus* was again an abundant natural predator in our treatments,

however in 2021, it was sampled more frequently in late-planted buckwheat and the weedy-fallow (Figure 5b).

Abundance of beneficial arthropods in crimson clover, field pea, and the weedy-fallow were lower than all other treatments in 2020 and 2021, with exception to the weedy-fallow in the late-planted cover crop trials of 2021. This lesser beneficial insect abundance was likely attributed to low floral abundance and reduced accessibility to pollen and nectar by flower morphology (Solomon and Ventaka, 2021). Peas tend to have small, fused petals called keel, forming a pocket that conceal the anthers, meaning that bees must have both strength and skill to expose the anthers. Because bee strength is correlated with weight, small bees are not capable of accessing nectar hidden at the base of keel petals (Cordoba and Cocucci, 2011; Solomon and Ventaka, 2021). In 2020, Phacelia had highest abundance of total beneficial arthropods ($P < 0.001$) relative to sunflower and oats, crimson clover, field pea and oats, the weedy fallow, and early-planted buckwheat (Figure 6a). However, this was not different from late-planted buckwheat. Most treatments had similar diversity ($P < 0.005$), except for field pea, early-planted crimson clover and late-planted phacelia (diversity data not illustrated). Treatments with greatest richness were buckwheat, the weedy-fallow, and early-planted phacelia compared to all other treatments ($P < 0.05$). Evenness was similar among treatments, except for early-planted crimson clover and late-planted phacelia and buckwheat ($P < 0.005$). In 2021, late-planted buckwheat had greatest total beneficial arthropod abundance ($P < 0.001$), followed by the weedy-fallow and phacelia, which

were both statistically similar (Figure 6b). Early-planted buckwheat trended towards greater diversity ($P < 0.001$), but was not dissimilar from late-planted field pea and the weedy-fallow (diversity data not illustrated). Buckwheat had greater richness than all other treatments ($P < 0.001$), except for the weedy-fallow in the late-planting of cover crops. Evenness was similar among early-planted buckwheat, crimson clover, and the weedy-fallow and late-planted field pea. Although the weedy-fallow may have supported similar diversity, richness and evenness to some flowering cover crops, it supported overall less abundance of beneficial arthropods.

Abundance, Diversity, Richness, and Evenness: Observational Assessments

On average, the total number of observed arthropods across all treatments, planting times and locations were 1,276 in 2020 and 1,479 in 2021, of which 83% (1,062) and 59% (867), respectively, were classified as beneficial arthropods. Beneficial specimens in 2020 were subset into 29 taxonomic groups, including one class (Arachnida), one order (Odonata), two superfamilies (Apoidea and Parasitica), 16 families, six genera, and three species (Table 5). Syrphidae (41%) and *Apis mellifera* (26%) comprised more than 65% of all specimens collected across all plant species and planting dates, followed by *Lasioglossum* (7%) and *Bombus* (6%). Syrphidae had the highest relative abundance in most treatments and locations, except for late-planted buckwheat and field pea and oat mixture in both locations and phacelia and sunflower and oat mixture in StP. *Orius insidiosus* and *Bombus* spp. had greatest relative abundance in sunflower and oat, and

Apis mellifera and *Lasioglossum* in phacelia. Thrips populations have also shown to increase when planting sole sunflower, as well as intercropping with vegetables (Legaspi and Baez, 2008). Our results show a sunflower and oat mixture can also act as insect reservoir for beneficial arthropods, including *O. insidiosus*, a predatory hemipteran of soft-bodied insects, such as thrips. In 2021, specimens were subset into one class (Arachnida), one order (Odonata), one superfamily (Parasitica), and 19 families (Table 6). Apidae (18%), Syrphidae (17%), and Halictidae (13%) comprised more than 45% of all specimens collected in StP and BRF across all plant species and planting dates. Abundant families were further identified into lower taxonomic levels. Apoidea specimens were identified to one family, including Andrenidae, and five genera, including *Agapostemon*, *Apis*, *Bombus, Halictus*, *Hylaeus*, and *Lasioglossum*. Bee genera with lower abundances, including *Nomada* and *Osmia*, or difficult to identify bees were grouped into "Other Apoidea" (Figure 7b). Syrphids were identified to six genera, including *Allograpta, Eristalis, Eupeodes, Platycheirus, Sphaerophoria,* and *Toxomerus*, while difficult to identify syrphids were grouped into "Other Syrphidae" (Figure 8b). Lady beetles were identified to four genera, including *Coccinella, Coleomegilla, Harmonia,* and *Hippodamia*, while difficult to identify lady beetles were grouped into "Other Coccinellidae" (Figure 9). Arthropod abundance observed in WE totaled 58 specimens, which were identified into one class (Arachnida) and 11 families (Table 7). Syrphidae comprised 50% of all observations across all plant species and planting dates, followed by Coccinellidae (16%) and Andrenidae (15%).

Similar to vacuum samples, crimson clover and field pea had lowest overall beneficial arthropod abundance in all locations, plantings, and years. Conversely, in 2020 (Figure 10a), late-planted buckwheat and early-planted phacelia had greatest beneficial arthropod abundance at StP, whereas at BRF, buckwheat in both early and late plantings had greatest abundance compared to other treatments ($P < 0.001$). In 2021, early- and late-planted buckwheat had greatest beneficial arthropod abundance in all three locations compared to all other treatments (Figure 10b), except for early-planted phacelia at StP ($P < 0.001$) and the weedy-fallow at WE (Figure 11). WE results were illustrated separately to StP and BRF due to public participation in scientific research, who identified less arthropod visitation to flowering cover crops and the weedy-fallow control. Greater beneficial arthropod abundance of predominant taxa groups, including Syrphidae and Apoidea, known to prefer buckwheat and phacelia, may be associated with greater abundance in these cover crops for arthropod collection methods (White et al., 1995). In 2020, the weedy-fallow in late-planted cover crop trials at StP showed greater diversity than all other treatments; whereas all early-planted treatments had comparable diversity, except for field pea ($P < 0.05$) (diversity data not illustrated). At BRF, buckwheat had higher diversity, but was not dissimilar to early-planted phacelia and the weedy-fallow in late-planted trials ($P < 0.005$). Early-planted phacelia, late-planted buckwheat and the weedy-fallow in late-planted trials had higher richness than other treatments at StP ($P < 0.05$). Whereas, at BRF, buckwheat had greater richness than other treatments ($P < 0.001$). Evenness was consistently higher in late-planted field pea and the weedy-fallow in late-planted trials at both locations, in addition to early-planted crimson clover at BRF

($P < 0.05$). In 2021, early- and late-planted buckwheat showed greater diversity and richness than other treatments at both StP and BRF, except for the weedy-fallow in early- and late-planted trials at StP showing similar diversity (diversity data not illustrated). All treatments at WE, expect for late-planted phacelia, had similar diversity ($P < 0.05$). Whereas only early-planted phacelia, early- and late-planted buckwheat and the weedy-fallow in early- and late-plantings had similar richness ($P < 0.05$). Evenness was consistent throughout treatments at all three locations, except for late-planted phacelia at all three locations ($P < 0.05$).

CONCLUSIONS

Some summer cover crops attracted an increased abundance of beneficial arthropods compared to a weedy fallow control; including predominant taxa such as Syrphidae (syrphid flies), particularly *Toxomerus marginatus*, a known natural predator as larva and pollinator as adult, Apoidea, specifically *Apis mellifera*, *Bombus* spp., and *Lasioglossum* spp., all considered efficient pollinators, and *Orius insidiosus* (minute pirate bug), a predator of soft-bodied insects, including common agricultural pests such as aphids and thrips. Out of all cover crop treatments, buckwheat showed consistency to obtain greater beneficial arthropod visitation, while also displaying greater, diversity and richness in both collection methods and locations. Although phacelia had comparable, or even greater, abundance, diversity, and richness to buckwheat depending on the year, this was

only observed at StP. As we saw in our results, beneficial arthropods demonstrate preference of some cover crop species over others (Hinds and Babercheck, 2020). Specifically, phacelia showed support towards native bees, particularly *Lasioglossum* species, as well as syrphid flies and minute pirate bugs. Both *Lasioglossum* spp. and syrphid flies have been documented to visit and prefer phacelia plants to other flowering plants (White et al., 1995; Wilson et al., 2018). Buckwheat also supported bees, with most visitations attributed to honey bees. Additionally, other beneficial arthropods that were present on flowering buckwheat were predators and parasitoids, including syrphid flies, lady beetles, vespid wasp, and parasitic wasps, providing potential biological control capacity. A study by Araj et al. in 2008, showed buckwheat floral nectar significantly influenced a parasitoid's potential to reduce herbivory host populations in alfalfa. Although sunflower only flowered briefly at the end of the late planting in both years at StP, it displayed potentials to act as a reservoir for predatory hemipterans. Depending on the planting season, year, and location, the weedy-fallow exhibited comparable abundance, diversity, richness, and evenness to some cover crop treatments. However, the functional groups primarily observed in this control treatment tended to be predatory and parasitic arthropods, with few to no pollinator visits recorded. Whereas other flowering cover crops, including buckwheat, phacelia, and sunflower, had a diversified functional group visitation that included all three functionalities under observation. Providing greater diversity of flowering resources may promote visitation of diverse arthropods. Further research exploring beneficial and pest populations in vegetable fields near cover crops, or vegetable rotations following cover crops, could

provide greater clarity of trophic level interactions between cover crops and increased beneficial arthropod functionality, including crop pollination and natural controls (Landis et al., 2005; Hinds and Barbercheck, 2020). Pollination dependent plants can benefit from cover crop planting proximities that flower before and after cash crops and support greater bee density and diversity (Blauuw and Isaacs, 2014). Furthermore, the results obtained from two arthropod data sampling methods indicate observational sampling, which eradicates impacts created on sampled populations, can be as effective and provide similar results for abundance, diversity, richness, and evenness assessments. However, some challenges presented from observational sampling include a steep learning curve to appropriately identify arthropods that are constantly moving or specimens that are extremely small and need to be viewed under a microscope to identify to family or lower taxonomic levels. Additionally, both methods may have favored aerial predominant taxa groups observed in our data, including Syrphidae and Apoidea. These groups are also known to prefer buckwheat and phacelia, potentially associated with greater abundance in these cover crops for both arthropod collection methods. Overall, summer-planted flowering cover crops provide valuable and essential resources, such as pollen, nectar, and alternate host species, particularly during greater reproduction and energy consumption periods, and are crucial for the sustenance, conservation, longevity, and fecundity of beneficial arthropods (Scarratt, 1994; Michaud and Qureshi, 2005; Hopwood et al., 2016). Improving flowering resource accessibility in agriculture-intensive fields by increasing cover crop diversity can also decrease the distance between natural habitats, ultimately supporting conservation efforts to protect beneficial arthropods.

TABLES AND FIGURES

Table 1. Common and scientific name of cover crop and weed species included in treatment groups, separated by commas. Seeding rate recommended by seed source, given in kg per hectare.

Treatment	Scientific name	Seeding rate (kg·ha^{-1})	Source
Buckwheat	*Fagopyrum esculentum* Moench	101	Albert Lea Seeds (organic)
Phacelia	*Phacelia tanacetifolia* Bendth.	14	Albert Lea Seeds (conventional)
Crimson clover	*Trifolium incarnatum* L.	38	Albert Lea Seeds (organic)
Field pea and Oat	*Pisum sativum* subsp. *Arvense* L. and *Avena sativa* L.	118, 105	Albert Lea Seeds (organic)
Sunflower and Oat	*Helianthus annuus* L. and *Avena sativa* L.	17, 105	Albert Lea Seeds (organic--oat / conventional--sunflower)
Weedy-fallow	*Amaranthus retroflexus, Chenopodium album, Thlaspi arvense, Galinsoga* sp., *Setaria viridis*		

Table 2. Field operation dates in 2020 and 2021 with day and month separated by a hyphen. Multiple dates on the same month (separated by a comma) and on different months (separated by a semi colon) within a cell indicate repetition of the operation. Operations listed by planting time (Early or Late Planting).

	Date	
Operation	**2020**	**2021**
Cover crop and lettuce planting (Early)	11, 12-May	3, 4, 18-May
Cover crop and broccoli planting (Late)	20, 29-July	28-June; 8, 21-July
Flower and arthropod sampling (Early)	17-June – 10-July	10-June – 21-July
Flower and arthropod sampling (Late)	20-August – 9-October	3-August – 6-October
Mowed cover crops (Early)	9, 13-July	13, 16, 21-July

Table 3. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of vacuum collections across six treatments by planting time (Early/Late) at St. Paul in 2020. Taxa listed alphabetically by class, order, and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

	Buckwheat				Crimson Clover				Oats and Field Peas			
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	0.3	0.3	**2**	**1**	--	--	--	--	--	--	--	--
Coleoptera												
Coccinellidae	0.8	1.5	**5**	**4**	--	--	--	--	0.3	--	**5**	--
Diptera												
Dolichopodidae	--	--	--	--	--	--	--	--	--	--	--	--
Tachinidae	--	0.3	--	**1**	--	--	--	--	--	--	--	--
Syrphidae	7.5	0.8	**53**	**2**	0.8	--	**25**	--	3.5	--	**70**	--
Hemiptera												
Anthocoridae	2.5	2.8	**18**	**7**	--	--	--	--	0.3	--	**5**	--
Hymenoptera												
Apidae	0.8	27.3	**5**	**71**	--	--	--	--	--	0.5	--	**100**
Braconidae	0.3	--	**2**	--	--	--	--	--	--	--	--	--
Halictidae	1	0.8	**7**	**2**	0.3	--	**8**	--	--	--	--	--
Ichneumonidae	--	0.3	--	**1**	0.8	--	**25**	--	0.3	--	**5**	--
Encyrtidae	0.5	--	**4**	--	--	--	--	--	--	--	--	--
Eulophidae	--	--	--	--	--	--	--	--	0.3	--	**5**	--
Mymaridae	--	0.8	--	**2**	1.0	--	**33**	--	--	--	--	--
Platygastridae	--	--	--	--	--	--	--	--	0.3	--	**5**	--
Torymidae	--	--	--	--	--	--	--	--	--	--	--	--
Pteromalidae	0.5	0.3	**4**	**1**	--	--	--	--	--	--	--	--
Vespidae	--	3.3	--	**8**	0.3	--	**8**	--	--	--	--	--
Neuroptera												
Chrysopidae	--	0.3	--	**1**	--	--	--	--	--	--	--	--
Thysanoptera												
Phlaeothripidae	0.3	--	**2**	--	--	--	--	--	0.3	--	**5**	--
Total	14.3	38.3			5.0	0			5.0	0.5		

Table 3. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of vacuum collections across six treatments by planting time (Early/Late) at St. Paul in 2020. Taxa order alphabetically by class, order, and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Total numbers on the far right indicate summed values specific to that row.

	Phacelia				Sunflower and Oats				Weedy-fallow				
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total
Arachnida	--	0.5	--	**2**	--	--	--	--	0.3	0.3	**3**	**3**	1.5
Coleoptera													
Coccinellidae	0.8	--	**2**	--	--	0.5	--	**3**	0.8	1.3	**8**	**14**	5.8
Diptera													
Dolichopodidae	--	--	--	--	--	--	--	--	0.3	0.8	**3**	**8**	1.0
Tachinidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Syrphidae	4.8	0.5	**13**	**2**	--	0.3	--	**1**	3.3	2	**35**	**20**	23.3
Hemiptera													
Anthocoridae	0.8	5.3	**2**	**17**	--	7.3	--	**41**	2.5	0.5	**27**	**5**	21.8
Hymenoptera													
Apidae	19.5	22.3	**53**	**74**	--	5.8	--	**33**	0.3	1.5	**3**	**16**	77.8
Braconidae	--	--	--	--	--	--	--	--	0.5	--	**5**	--	0.8
Halictidae	10.8	0.3	**29**	**1**	--	--	--	--	0.3	1	**3**	**11**	14.3
Ichneumonidae	--	--	--	--	--	--	--	--	--	--	--	--	1.3
Encyrtidae	--	0.3	--	**1**	--	--	--	--	--	--	--	--	0.8
Eulophidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Mymaridae	--	0.8	--	**2**	--	--	--	--	--	0.8	--	**8**	3.3
Platygastridae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Torymidae	--	--	--	--	--	--	--	--	0.3	--	**3**	--	0.3
Pteromalidae	--	0.3	--	**1**	--	0.8	--	**4**	0.5	0.5	**5**	**5**	2.8
Vespidae	--	0.3	--	**1**	--	3	--	**17**	--	0.8	--	**8**	7.5
Neuroptera													
Chrysopidae	0.3	--	**1**	--	--	--	--	--	--	--	--	--	0.5
Thysanoptera													
Phlaeothripidae	--	--	--	--	--	--	--	--	0.5	--	**5**	--	1.0
Total	36.8	30.3			0	17.5			9.3	9.3			164.0

Table 4. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of vacuum collections across six treatments by planting time (Early/Late) at St. Paul in 2021. Taxa listed alphabetically by class, order, and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

	Buckwheat				Crimson Clover				Oats and Field Peas			
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	0.3	0.8	**1**	**1**	1.0	--	**12**	--	--	0.3	--	**1**
Coleoptera												
Cantharidae	--	20.3	--	**17**	--	--	--	--	--	--	--	--
Coccinellidae	4.0	4.5	**13**	**4**	0.3	--	**3**	--	--	4.3	--	**22**
Diptera												
Dolichopodidae	0.5	0.3	**2**	**0**	0.3	--	**3**	--	--	0.3	--	**1**
Syrphidae	6.0	0.3	**20**	**0**	--	--	--	--	--	0.3	--	**1**
Hemiptera												
Anthocoridae	6.0	66.0	**20**	**55**	4.5	--	**53**	--	--	3.8	--	**19**
Geocoridae	--	--	--	--	--	--	--	--	--	--	--	--
Nabidae	--	0.3	--	**0**	--	--	--	--	--	0.3	--	**1**
Reduviidae	--	--	--	--	--	--	--	--	--	--	--	--
Hymenoptera												
Andrenidae	0.5	--	**2**	--	--	--	--	--	--	--	--	--
Apidae	5.8	10.0	**19**	**8**	0.3	--	**3**	--	--	0.8	--	**4**
Bethylidae	--	0.3	--	**0**	--	--	--	--	--	--	--	--
Braconidae	1.5	0.3	**5**	**0**	--	--	--	--	--	1.5	--	**8**
Colletidae	--	0.5	--	**0**	--	--	--	--	--	--	--	--
Crabronidae	0.3	0.8	**1**	**1**	--	--	--	--	--	--	--	--
Halictidae	3.0	0.3	**10**	**0**	--	--	--	--	--	--	--	--
Ichneumonidae	--	0.3	--	**0**	0.5	--	**5**	--	--	1.0	--	**5**
Encyrtidae	0.5	2.8	**2**	**2**	--	--	--	--	--	0.3	--	**1**
Eulophidae	--	1.3	--	**1**	--	--	--	--	--	1.0	--	**5**
Eurytomidae	0.8	2.8	**2**	**2**	--	--	--	--	--	--	--	--
Mymaridae	1.5	3.3	**5**	**3**	1.3	--	**15**	--	--	5.0	--	**25**
Trichogrammatidae	--	--	--	--	0.3	--	**3**	--	--	--	--	--
Pteromalidae	--	2.0	--	**2**	0.3	--	**3**	--	--	0.5	--	**3**
Vespidae	--	2.0	--	**2**	--	--	--	--	--	--	--	--
Neuroptera												
Chrysopidae	--	1.0	--	**1**	--	--	--	--	--	0.8	--	**4**
Thysanoptera												
Phlaeothripidae	--	0.3	--	**0**	--	--	--	--	--	--	--	--
Total	30.5	119.8			8.5	0			0	19.8		

Table 4. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of vacuum collections across six treatments by planting time (Early/Late) at St. Paul in 2021. Taxa listed alphabetically by class, order, and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Total numbers on the far right indicate summed values specific to that row.

	Phacelia				Sunflower and Oats				Weedy-fallow				
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total
Arachnida	0.3	2.5	**1**	**4**	--	2.3	--	**6**	0.5	3.0	**3**	**4**	10.8
Coleoptera													
Cantharidae	--	--	--	--	--	--	--	--	--	0.5	--	**1**	20.8
Coccinellidae	0.5	--	**1**	--	--	1.3	--	**3**	1.5	2.8	**10**	**3**	19.0
Diptera													
Dolichopodidae	--	0.3	--	**0**	--	--	--	--	1.5	0.8	**10**	**1**	3.8
Syrphidae	3.3	1.0	**9**	**2**	--	--	--	--	1.3	0.3	**8**	**0**	12.3
Hemiptera													
Anthocoridae	3.3	14.0	**9**	**22**	--	22.0	--	**56**	2.0	55.8	**13**	**69**	177.3
Geocoridae	--	0.5	--	**1**	--	--	--	--	--	--	--	--	0.5
Nabidae	--	--	--	--	--	--	--	--	0.8	0.5	**5**	**1**	1.8
Reduviidae	--	0.3	--	**0**	--	--	--	--	--	--	--	--	0.3
Hymenoptera													
Andrenidae	--	--	--	--	--	--	--	--	--	--	--	--	0.5
Apidae	7.3	37.0	**20**	**61**	--	7.8	--	**20**	0.3	--	**2**	--	69.0
Bethylidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Braconidae	1.0	0.3	**3**	**0**	--	--	--	--	0.5	0.5	**3**	**1**	5.5
Colletidae	--	0.3	--	**0**	--	--	--	--	--	--	--	--	0.8
Crabronidae	--	0.3	--	**0**	--	--	--	--	--	0.3	--	**0**	1.5
Halictidae	19.8	0.8	**54**	**1**	--	0.5	--	**1**	0.3	0.8	**2**	**1**	25.3
Ichneumonidae	--	--	--	--	--	0.3	--	**1**	--	0.3	--	**0**	2.3
Encyrtidae	--	0.5	--	**1**	--	1.5	--	**4**	--	0.8	--	**1**	6.3
Eulophidae	--	1.0	--	**2**	--	1.3	--	**3**	0.3	1.0	**2**	**1**	5.8
Eurytomidae	--	0.5	--	**1**	--	--	--	--	--	0.5	--	**1**	4.5
Mymaridae	0.5	3.5	**1**	**6**	--	1.3	--	**3**	5.5	8.8	**36**	**11**	30.5
Trichogrammatidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Pteromalidae	--	--	--	--	--	0.8	--	**2**	0.3	1.5	**2**	**2**	5.3
Vespidae	0.8	0.3	**2**	**0**	--	0.3	--	**1**	--	0.5	--	**1**	3.8
Neuroptera													
Chrysopidae	--	0.3	--	**0**	--	--	--	--	0.5	3.0	**3**	**4**	5.5
Thysanoptera													
Phlaeothripidae	--	--	--	--	--	--	--	--	0.3	--	**2**	--	0.5
Total	36.5	63.0			0	39.0			15.3	81.3			413.5

Table 5. Total number of individuals and relative abundance (RA %-- in bold) for each taxon encountered in observational assessments across six treatments by planting time (Early—E/Late—L) at St. Paul (StP) and Big River Farms (BRF) in 2020. Taxa listed alphabetically by class, order, superfamily* (indent), family (indent), genus (in italic and indent), and species (in italic and indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

	Buckwheat								Crimson Clover							
	StP				BRF				StP				BRF			
	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	--	--	**--**	**--**	--	0.5	**--**	**1**	0.3	--	**3**	**--**	0.8	--	**1**	**--**
Coleoptera																
Cantharidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	--	--
Coccinellidae	2.8	2.8	**2**	**2**	0.8	5.5	**1**	**7**	0.8	--	**9**	**--**	--	--	--	--
Diptera																
Dolichopodidae	--	1.3	**--**	**1**	--	0.8	**--**	**1**	--	--	**--**	**--**	--	--	**--**	**--**
Syrphidae	90.3	15.0	**78**	**9**	77.3	29.0	**64**	**39**	6.0	--	**69**	**--**	5.0	--	**80**	**--**
Tachinidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Hemiptera																
Nabidae	--	--	**--**	**--**	--	--	**--**	**--**	0.3	--	**3**	**--**	--	--	**--**	**--**
Orius insidiosus	--	--	**--**	**--**	--	0.8	**--**	**1**	--	--	**--**	**--**	--	--	--	--
Hymenoptera																
Andrenidae	--	--	**--**	**--**	20.3	--	**17**	**--**	--	--	**--**	**--**	--	--	--	--
Apis mellifera	12.5	110.5	**11**	**67**	1.0	0.8	**1**	**1**	--	--	**--**	**--**	--	--	--	--
Bombus	0.5	8.0	**0**	**5**	3.8	0.8	**3**	**1**	--	--	**--**	**--**	--	--	--	--
Braconidae	0.8	0.3	**1**	**0**	--	1.0	**--**	**1**	--	--	**--**	**--**	0.3	--	**3**	**--**
Ceratina	--	0.3	**--**	**0**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Colletidae	--	--	**--**	**--**	0.3	--	**0**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Crabronidae	--	--	**--**	**--**	1.3	0.8	**1**	**1**	--	--	**--**	**--**	--	--	**--**	**--**
Halictidae	4.3	0.8	**4**	**0**	1.8	1.0	**1**	**1**	--	--	**--**	**--**	--	--	--	--
Hylaeus	--	--	**--**	**--**	--	0.3	**--**	**0**	--	--	**--**	**--**	--	--	--	--
Ichneumonidae	--	0.3	**--**	**--**	--	0.5	**--**	**1**	--	--	**--**	**--**	--	--	--	--
Lasioglossum	3.8	2.0	**3**	**1**	4.0	0.5	**3**	**1**	0.3	--	**3**	**--**	--	--	--	--
Megachilidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	--	--
Nomada	0.3	--	**0**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	--	--
Other Apoidea*	--	--	**--**	**--**	0.8	--	**1**	**--**	--	--	**--**	**--**	--	--	--	--

Other Parasitica*	0.8	0.8	**1**	**0**	5.0	1.0	**4**	**1**	0.8	--	**9**	--	0.3	--	**4**	--
Polistes dominula	0.3	19.8	**0**	**12**	1.3	1.8	**1**	**2**	0.3	--	**3**	--	--	--	--	--
Pompilidae	--	0.3	--	**0**	0.3	--	**0**	--	--	--	--	--	--	--	--	--
Sphecidae	--	--	--	--	0.3	0.3	**0**	**0**	--	--	--	--	--	--	--	--
Vespidae	--	2.5	--	**2**	2.8	30.0	**2**	**40**	--	--	--	--	--	--	--	--
Neuroptera																
Chrysopidae	--	0.3	--	**0**	--	0.3	--	**0**	0.3	--	**3**	--	--	--	--	--
Odonata	--	--	--	--	0.5	--	**0**	--	--	--	--	--	--	--	--	--
Total	464	626			121.0	75.3			8.8	0.0			6.3	0.0		

Table 5. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of observational assessments across six treatments by planting time (Early—E/Late—L) at St. Paul (StP) and Big River Farms (BRF) in 2020. Taxa listed alphabetically by class, order, superfamily* (indent), family (indent), genus (in italic and indent), and species (in italic and indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

	Field Pea								Phacelia							
	StP				BRF				StP				BRF			
	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	0.3	--	**1**	**--**	1.0	0.8	**3**	**27**	0.3	--	**0**	--	--	--	--	--
Coleoptera																
Cantharidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Coccinellidae	2.0	0.3	**8**	**4**	0.5	0.3	**2**	**9**	1.3	--	**1**	--	0.3	--	**0**	--
Diptera																
Dolichopodidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--		--
Syrphidae	19.8	1.8	**81**	**30**	26.0	0.5	**83**	**18**	37.5	2.3	**25**	**2**	31.5	--	**57**	--
Tachinidae	--	--	**--**	**--**	0.3	--	**1**	--	--	--	**--**	**--**	--	--		--
Hemiptera																
Nabidae	--	--	**--**	**--**	0.3	--	**1**	--	--	0.3	**--**	**0**	--	--	**--**	**--**
Orius insidiosus	--	0.8	**--**	**13**	--	0.5	**--**	**18**	--	--	**--**	**--**	--	--	**--**	**--**
Hymenoptera																
Andrenidae	--	--	**--**	**--**	--	--	**--**	**--**	0.3	--	**0**	--	--	--	**--**	**--**
Apis mellifera	--	1.8	**--**	**30**	--	--	**--**	**--**	43.3	89.5	**28**	**87**	--	--	**--**	**--**
Bombus	0.5	--	**2**	**--**	0.8	--	**2**	**--**	21.8	9.8	**14**	**9**	7.0	--	**13**	**--**
Braconidae	0.5	0.3	**2**	**4**	--	--	**--**	**--**	2.0	--	**1**	**--**	0.5	--	**1**	**--**
Ceratina	--	--	**--**	**--**	--	--	**--**	**--**	0.5	--	**0**	**--**	--	--	**--**	**--**
Colletidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Crabronidae	--	--	**--**	**--**	0.5	--	**2**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Halictidae	--	0.3	**--**	**4**	0.3	--	**1**	**--**	2.3	0.5	**1**	**0**	1.8	--	**3**	**--**
Hylaeus	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Ichneumonidae	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**	--	--	**--**	**--**
Lasioglossum	1.5	--	**6**	**--**	--	--	**--**	**--**	43.3	--	**28**	**--**	12.8	--	**23**	**--**

Megachilidae	--	--	--	--	0.3	--	**1**	--	0.3	--	**0**	--	--	--	--	--
Nomada	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Other Apoidea*	--	--	--	--	--	--	--	--	--	--	--	--	0.3	--	**0**	--
Other Parasitica	--	0.3	**4**	--	--	0.8	--	**27**	0.3	--	**0**	--	--	--	--	--
Polistes dominula	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Pompilidae	--	0.3	**4**	--	--	--	--	--	--	0.3	--	**0**	--	--	--	--
Sphecidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Vespidae	--	0.3	**4**	--	--	--	--	--	0.3	0.3	**0**	**0**	1.0	--	**2**	--
Neuroptera																
Chrysopidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Odonata	--	--	--	--	1.5	--	**5**	--	--	--	--	--	--	--	--	--
Total	24.5	5.8			31.3	2.8			153.0	102.8			55.0	0.0		

Table 5. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of observational assessments across six treatments by planting time (Early—E/Late—L) at St. Paul (StP) and Big River Farms (BRF) in 2020. Taxa listed alphabetically by class, order, superfamily* (indent), family (indent), genus (in italic and indent), and species (in italic and indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Total numbers on the far right indicate summed values by location and specific to that row. Continued.

	Sunflower							
	StP				BRF			
	E	L	E	L	E	L	E	L
Taxa	Total		RA(%)		Total		RA(%)	
Arachnida	--	--	--	--	--	--	--	--
Coleoptera								
Cantharidae	--	--	--	--	--	--	--	--
Coccinellidae	--	2.0	--	**3**	--	--	--	--
Diptera								
Dolichopodidae	--	--	--	--	--	--	--	--
Syrphidae	--	3.0	--	**5**	--	--	--	--
Tachinidae	--	--	--	--	--	--	--	--
Hemiptera								
Nabidae	--	--	--	--	--	--	--	--
Orius insidiosus	--	28.0	--	**49**	--	--	--	--
Hymenoptera								
Andrenidae	--	--	--	--	--	--	--	--
Apis mellifera	--	10.0	--	17	--	--	--	--
Bombus	--	8.8	--	**15**	--	--	--	--
Braconidae	--	--	--	--	--	--	--	--
Ceratina	--	--	--	--	--	--	--	--
Colletidae	--	--	--	--	--	--	--	--
Crabronidae	--	--	--	--	--	--	--	--
Halictidae	--	0.3	--	**0**	--	--	--	--
Hylaeus	--	--	--	--	--	--	--	--
Ichneumonidae	--	--	--	--	--	--	--	--
Lasioglossum	--	--	--	--	--	--	--	--
Megachilidae	--	--	--	--	--	--	--	--
Nomada	--	--	--	--	--	--	--	--

Other Apoidea*	--	--	--	--	--	--	--	--
Other Parasitica*	--	2.0	--	**3**	--	--	--	--
Polistes dominula	--	0.8	--	**1**	--	--	--	--
Pompilidae	--	--	--	--	--	--	--	--
Sphecidae	--	--	--	--	--	--	--	--
Vespidae	--	2.5	--	**4**	--	--	--	--
Neuroptera								
Chrysopidae	--	--	--	--	--	--	--	--
Odonata	--	--	--	--	--	--	--	--
Total	0.0	57.3			0.0	0.0		

Table 5. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of observational assessments across six treatments by planting time (Early—E/Late—L) at St. Paul (StP) and Big River Farms (BRF) in 2020. Taxa listed alphabetically by class, order, superfamily* (indent), family (indent), genus (in italic and indent), and species (in italic and indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Total numbers on the far right indicate summed values by location and specific to that row.

	Weedy-fallow									
	StP				BRF					
	E	L	E	L	E	L	E	L	Total	Total
Taxa	Total		RA(%)		Total		RA(%)		StP	BRF
Arachnida	--	0.5	--	**3**	0.3	0.8	**1**	**3**	1.3	4.0
Coleoptera										
Cantharidae	--	0.3	--	**1**	--	--	--	--	0.3	0.0
Coccinellidae	1.0	3.8	**2**	**19**	1.0	4.3	**3**	**18**	16.5	12.5
Diptera										
Dolichopodidae	--	2.0	--	**10**	--	--	--	--	3.3	0.8
Syrphidae	45.3	6.8	**77**	**34**	31.8	11.8	**87**	**51**	227.5	212.8
Tachinidae	--	--	--	--	--	--	--	--	0.0	0.3
Hemiptera										
Nabidae	--	--	--	--	--	--	--	--	0.5	0.3
Orius insidiosus	--	0.5	--	**3**	--	--	--	--	29.3	1.3
Hymenoptera										
Andrenidae	--	--	--	--	--	--	--	--	0.3	20.3
Apis mellifera	3.0	2.3	**5**	**11**	--	0.8	--	**3**	272.8	2.5
Bombus	3.3	--	**6**	--	0.5	0.8	**1**	**3**	52.5	13.5
Braconidae	0.3	0.5	**0**	**3**	0.5	1.0	**1**	**4**	4.5	3.3
Ceratina	--	--	--	--	--	--	--	--	0.8	0.0
Colletidae	0.3	--	**0**	--	--	--	--	--	0.3	0.3
Crabronidae	--	--	--	--	0.3	--	**1**	--	0.0	2.8
Halictidae	1.0	0.3	**2**	**1**	--	1.0	--	**4**	9.5	5.8
Hylaeus	--	--	--	--	--	--	--	--	0.0	0.3
Ichneumonidae	--	0.3	--	**1**	--	0.5	--	**2**	0.5	1.0
Lasioglossum	3.0	0.8	**5**	**4**	1.5	1.3	**4**	**5**	54.5	20.0
Megachilidae	--	--	--	--	--	--	--	--	0.3	0.3
Nomada	0.5	--	**1**	--	--	--	--	--	0.8	0.0

Other Apoidea*	--	--	--	--	--	--	--	--	0.0	1.0
Other Parasitica*	1.0	0.8	**2**	**6**	0.5	0.5	**1**	**2**	7.0	8.0
Polistes dominula	--	0.3	--	**3**	--	--	--	--	21.5	3.0
Pompilidae	--	--	--	--	--	--	--	--	0.8	0.3
Sphecidae	--	--	--	--	--	--	--	--	0.0	0.5
Vespidae	--	0.3	--	**1**	--	0.5	--	**2**	6.0	34.3
Neuroptera										
Chrysopidae	--	--	--	--	--	0.3	--	**1**	0.5	0.5
Odonata	--	--	--	--	0.3	--	**1**	--	0.0	2.3
Total	58.5	19.8			36.5	23.3			710.8	351.3

Table 6. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of observational assessments across six treatments by planting time (Early—E/Late—L) at St. Paul (StP) and Big River Farms (BRF) in 2021. Taxa listed alphabetically by class, order, superfamily* (indent), and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

	Buckwheat								Crimson Clover							
	StP				BRF				StP				BRF			
	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	0.8	0.3	**1**	**0**	0.8	--	**1**	**--**	0.3	--	**5**	--	0.5	--	**50**	--
Coleoptera																
Cantharidae	--	64.3	--	**33**	--	3.5	--	**5**	--	--	--	--	--	--	--	--
Coccinellidae	8.8	24.0	**12**	**12**	3.0	3.5	**4**	**5**	0.3	--	**5**	--	--	--	--	--
Diptera																
Dolichopodidae	3.0	8.5	**4**	**4**	1.0	0.8	**1**	**1**	--	--	--	--	--	--	--	--
Syrphidae	23.5	12.3	**32**	**6**	24.8	6.5	**37**	**9**	0.3	--	**5**	--	--	--	--	--
Tachinidae	--	--	--	--	--	0.3	--	**0**	--	--	--	--	--	--	--	--
Hemiptera																
Anthocoridae	0.3	5.0	**0**	**3**	--	5.5	--	**7**	1.8	--	**35**	--	--	--	--	--
Nabidae	--	--	--	--	--	--	--	--	0.3	--	**5**	--	--	--	--	--
Reduviidae	--	--	--	--	--	0.5	--	**1**	--	--	--	--	--	--	--	--
Hymenoptera																
Andrenidae	2.0	--	**3**	--	13.5	--	**20**	--	--	--	--	--	--	--	--	--
Apidae	17.0	44.5	**23**	**23**	4.8	19.3	**7**	**26**	--	--	--	--	0.5	--	**50**	--
Braconidae	2.0	3.0	**3**	**2**	2.8	2.0	**4**	**3**	2.0	--	**40**	--	--	--	--	--
Chrysididae	--	--	--	--	--	0.3	--	**0**	--	--	--	--	--	--	--	--

Colletidae	--	0.8	--	**0**	--	0.3	--	**0**	--	--	--	--	--	--	--	--
Crabronidae	3.8	4.0	**5**	**2**	8.0	4.3	**12**	**6**	--	--	--	--	--	--	--	--
Halictidae	12	3.0	**16**	**2**	5.0	6.0	**7**	**8**	--	--	--	--	--	--	--	--
Ichneumonidae	0.3	2.3	**0**	**1**	1.0	--	**1**	--	--	--	--	--	--	--	--	--
Megachilidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Other Parasitica*	--	--	--	--	--	1.8	--	**2**	--	--	--	--	--	--	--	--
Vespidae	0.5	19.3	**1**	**10**	--	16.3	--	**22**	--	--	--	--	--	--	--	--
Neuroptera																
Chrysopidae	0.5	1.3	**1**	**1**	2.3	3.5	**3**	**5**	0.3	--	**5**	--	--	--	--	--
Odonata	--	--	--	--	0.5	--	**1**	--	--	--	--	--	--	--	--	--
Total	74.3	192.5			67.3	74.0			5.0	0			0.5	0		

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	Field Pea								Phacelia							
	StP				BRF				StP				BRF			
	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	--	1.0	--	**8**	0.3	--	**1**	--	0.5	--	**1**	--	0.5	--	**2**	--
Coleoptera																
Cantharidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Coccinellidae	--	8.0	--	**65**	13.5	0.3	**59**	**25**	1.0	0.3	**1**	**1**	--	--	--	--
Diptera																
Dolichopodidae	--	0.3	--	**2**	--	--	--	--	--	--	--	--	--	--	--	--
Syrphidae	--	0.3	--	**2**	4.0	0.5	**17**	**50**	11.5	1.0	**12**	**3**	9.0	--	**44**	--
Tachinidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Hemiptera																
Anthocoridae	--	--	--	--	--	--	--	--	--	1.0	--	**3**	--	--	--	--
Nabidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Reduviidae	--	--	--	--	0.3	--	**1**	--	--	0.3	--	**1**	--	--	--	--
Hymenoptera																
Andrenidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Apidae	--	0.8	--	**6**	0.3	--	**1**	--	8.5	34.5	**9**	**88**	1.3	--	**6**	--
Braconidae	--	0.5	--	**4**	1.3	--	**5**	--	--	--	--	--	1.5	--	**7**	--
Chrysididae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Colletidae	--	--	--	--	--	--	--	--	--	0.3	--	**1**	--	--	--	--
Crabronidae	--	--	--	--	0.3	--	**1**	--	--	--	--	--	--	--	--	--
Halictidae	--	--	--	--	0.3	--	**1**	--	74.0	1.5	**77**	**4**	6.8	--	**33**	--
Ichneumonidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Megachilidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Other Parasitica*	--	1.0	--	**8**	0.3	--	**1**	--	--	--	--	--	--	--	--	--
Vespidae	--	--	--	--	--	--	--	--	1.3	0.3	**1**	**1**	--	--	--	--
Neuroptera																
Chrysopidae	--	0.5	--	**4**	2.8	0.3	**12**	**25**	0.3	--	**0**	--	1.3	--	**6**	--
Odonata	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Total	0.0	12.3			23.0	1.0			97.0	39.0			20.3	0.0		

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	Sunflower								Weedy-fallow									
	StP				BRF				StP				BRF					
	E	L	E	L	E	L	E	L	E	L	E	L	E	L	E	L	Total	Total
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total		RA(%)		StP	BRF
Arachnida	--	0.3	--	**1**	--	--	--	--	1.5	0.5	**6**	**1**	0.8	1.0	**2**	**2**	5.3	3.5
Coleoptera																		
Cantharidae	--	--	--	--	--	--	--	--	--	0.5	--	**1**	--	--	--	--	64.8	35.5
Coccinellidae	--	1.3	--	**3**	--	--	--	--	3.0	11.5	**12**	**25**	0.8	4.5	**2**	**10**	58.0	25.5
Diptera																		
Dolichopodidae	--	0.3	--	**1**	--	--	--	--	3.5	3.8	**13**	**8**	--	0.3	--	**1**	19.3	2.0
Syrphidae	--	--	--	--	--	--	--	--	11.0	1.0	**42**	**2**	5.0	3.5	**16**	**7**	60.8	53.3
Tachinidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.0	0.3
Hemiptera																		
Anthocoridae	--	24.3	--	**49**	--	--	--	--	--	15.3	--	**33**	--	9.3	--	**20**	47.5	14.8
Nabidae	--	--	--	--	--	--	--	--	0.8	--	**3**	--	--	--	--	--	1.0	0.0
Reduviidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.3	0.8
Hymenoptera																		
Andrenidae	--	--	--	--	--	--	--	--	--	--	**1**	--	0.5	--	**2**	--	2.0	14.0
Apidae	--	18.8	--	**38**	--	--	--	--	0.5	9	**2**	**5**	--	--	--	--	126.8	25.8
Braconidae	--	0.3	--	**1**	--	--	--	--	1.5	--	**6**	--	20.3	2.8	**63**	**6**	9.3	30.5
Chrysididae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.0	0.3
Colletidae	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.0	0.3

Crabronidae	--	--	--	--	--	--	--	--	0.3	--	**1**	--	0.8	--	**2**	--	8.0	13.3
Halictidae	--	0.8	--	**2**	--	--	--	--	1.5	0.3	**6**	**1**	0.5	3.3	**2**	**7**	93.0	21.8
Ichneumonidae	--	--	--	--	--	--	--	--	--	0.3	--	**1**	--	1.8	--	**4**	2.8	2.8
Megachilidae	--	0.3	--	**1**	--	--	--	--	--	--	--	--	--	--	--	--	0.3	0.0
Other Parasitica*	--	3.5	--	**7**	--	--	--	--	0.3	0.8	**1**	**2**	0.8	0.8	**2**	**2**	5.5	3.5
Vespidae	--	0.3	--	**1**	--	--	--	--	0.3	1.0	**1**	**2**	--	1.0	--	**2**	22.8	17.3
Neuroptera																		
Chrysopidae	--	--	--	--	--	--	--	--	1.0	8.8	**4**	**19**	2.5	18.8	**8**	**40**	12.5	31.3
Odonata	--	--	--	--	--	--	--	--	1.0	--	**4**	--	0.3	--	**1**	--	1.0	0.8
Total	0	49.8			0	0			94	164			124	200			541.5	264.8

Table 7. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of observational assessments across six treatments by planting time (Early/Late) at White Earth Nation, Mahnomen in 2021. Taxa listed alphabetically by class, order, and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Continued.

	Buckwheat				Crimson Clover				Field Pea			
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)	
Arachnida	--	--	--	--	--	--	--	--	--	--	--	--
Coleoptera												
Coccinellidae	--	8.0	--	**52**	--	--	--	--	--	--	--	--
Diptera												
Dolichopodidae	0.8	--	**6**	--	--	--	--	--	--	--	--	--
Syrphidae	10.5	5.0	**78**	**32**	--	--	--	--	--	--	--	--
Hemiptera												
Nabidae	0.5	--	**4**	--	--	--	--	--	--	--	--	--
Hymenoptera												
Andrenidae	--	1.5	--	**10**	--	--	--	--	--	--	--	--
Apidae	1.0	0.5	**7**	**3**	--	--	--	--	--	--	--	--
Braconidae	0.3	--	**2**	--	--	--	--	--	--	--	--	--
Halictidae	0.3	0.3	**2**	**2**	--	--	--	--	--	--	--	--
Ichneumonidae	0.3	--	**2**	--	--	--	--	--	--	--	--	--
Vespidae	--	0.3	--	**2**	--	--	--	--	--	--	--	--
Neuroptera												
Chrysopidae	--	--	--	--	--	--	--	--	--	--	--	--
Total	13.5	15.5			0.0	0.0			0.0	0.0		

Table 7. Total number of individuals and relative abundance (RA %-- in bold) for each taxon of observational assessments across six treatments by planting time (Early/Late) at White Earth Nation, Mahnomen in 2021. Taxa listed alphabetically by class, order, and family (indent). Dash lines indicate that the taxon specific to that row was not found on flowers within the column. Total numbers at the bottom represent summed values specific to that column. Total numbers on the far right indicate summed values specific to that row.

	Phacelia				Sunflower				Weedy-fallow				
	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	Early	Late	
Taxa	Total		RA(%)		Total		RA(%)		Total		RA(%)		Total
Arachnida	0.3	--	**3**	--	--	--	--	--	--	--	--	--	0.3
Coleoptera													
Coccinellidae	--	--	--	--	--	0.5	--	**22**	0.5	0.5	**4**	**67**	9.5
Diptera													
Dolichopodidae	--	--	--	--	--	--	--	--	1.8	--	**15**	--	2.5
Syrphidae	4.5	--	**58**	--	--	0.5	--	**22**	8.3	0.3	**70**	**33**	29.0
Hemiptera													
Nabidae	--	--	--	--	--	--	--	--	0.3	--	**2**	--	0.8
Hymenoptera													
Andrenidae	--	6.3	--	**96**	--	0.5	--	**22**	0.3	--	**2**	--	8.5
Apidae	2.0	0.3	**26**	**4**	--	0.8	--	**33**	0.3	--	**2**	--	4.8
Braconidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Halictidae	0.5	--	**6**	--	--	--	--	--	--	--	--	--	1.0
Ichneumonidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Vespidae	--	--	--	--	--	--	--	--	--	--	--	--	0.3
Neuroptera													
Chrysopidae	0.5	--	**6**	--	--	--	--	--	0.5	--	**4**	--	1.0
Total	7.8	6.5			0.0	2.3			11.8	0.8			58.0

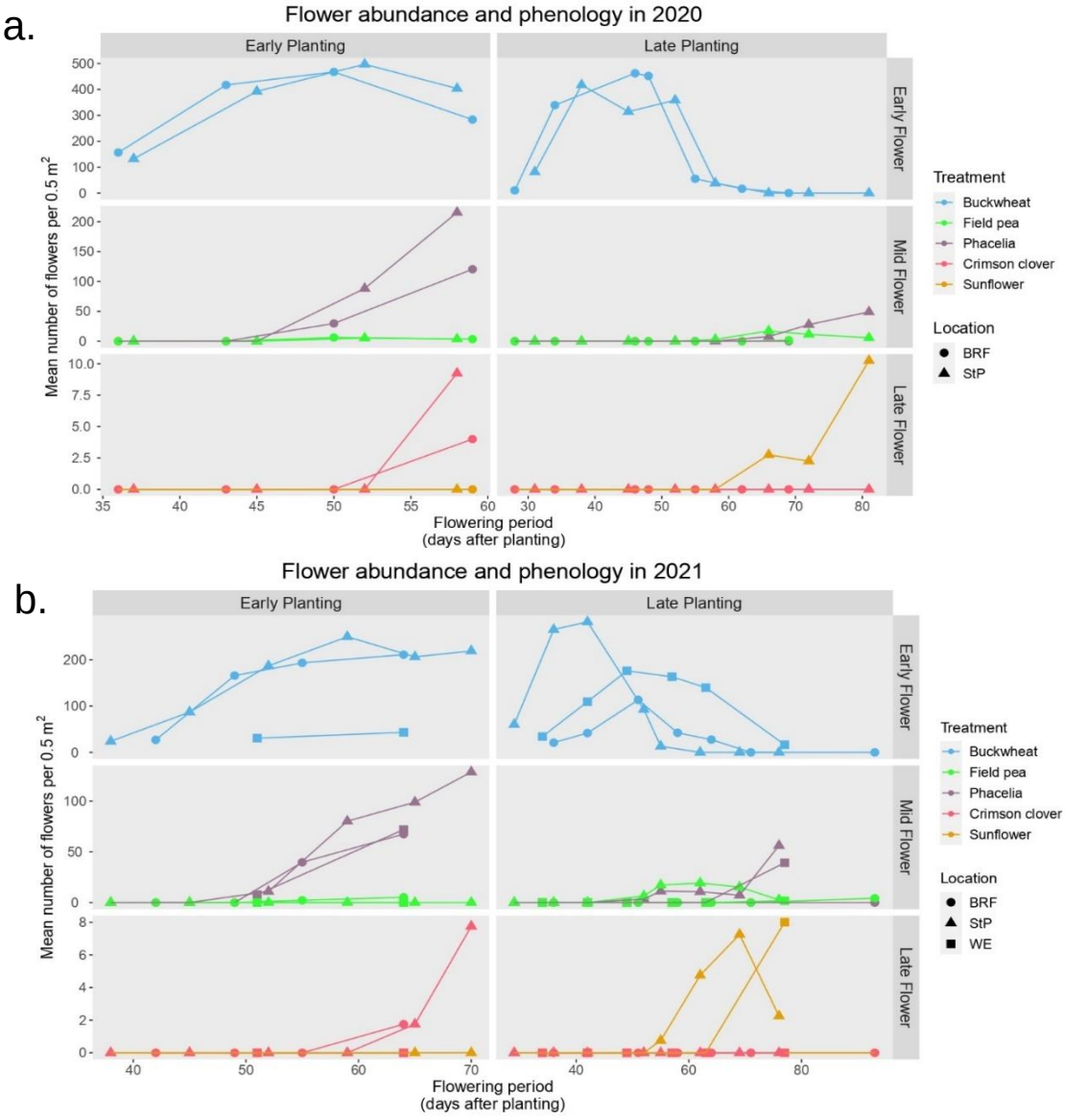

Figure 1a and 1b. Cover crop flower phenology as described by abundance of mean floral number per 0.5 m^2 and flowering period (floral bloom to floral senescence) illustrated in days after planting. Treatment values are divided into planting times (Early or Late Planting), categorized by flowering time (Early, Mid, or Late Flower), and located at **a)** St. Paul and Big River Farms (BRF) in 2020 and **b)** St. Paul (StP), Big River Farms and White Earth (WE) in 2021. Total values in the y-axis vary by flowering time; location represented by geometrical figures and treatment by colors

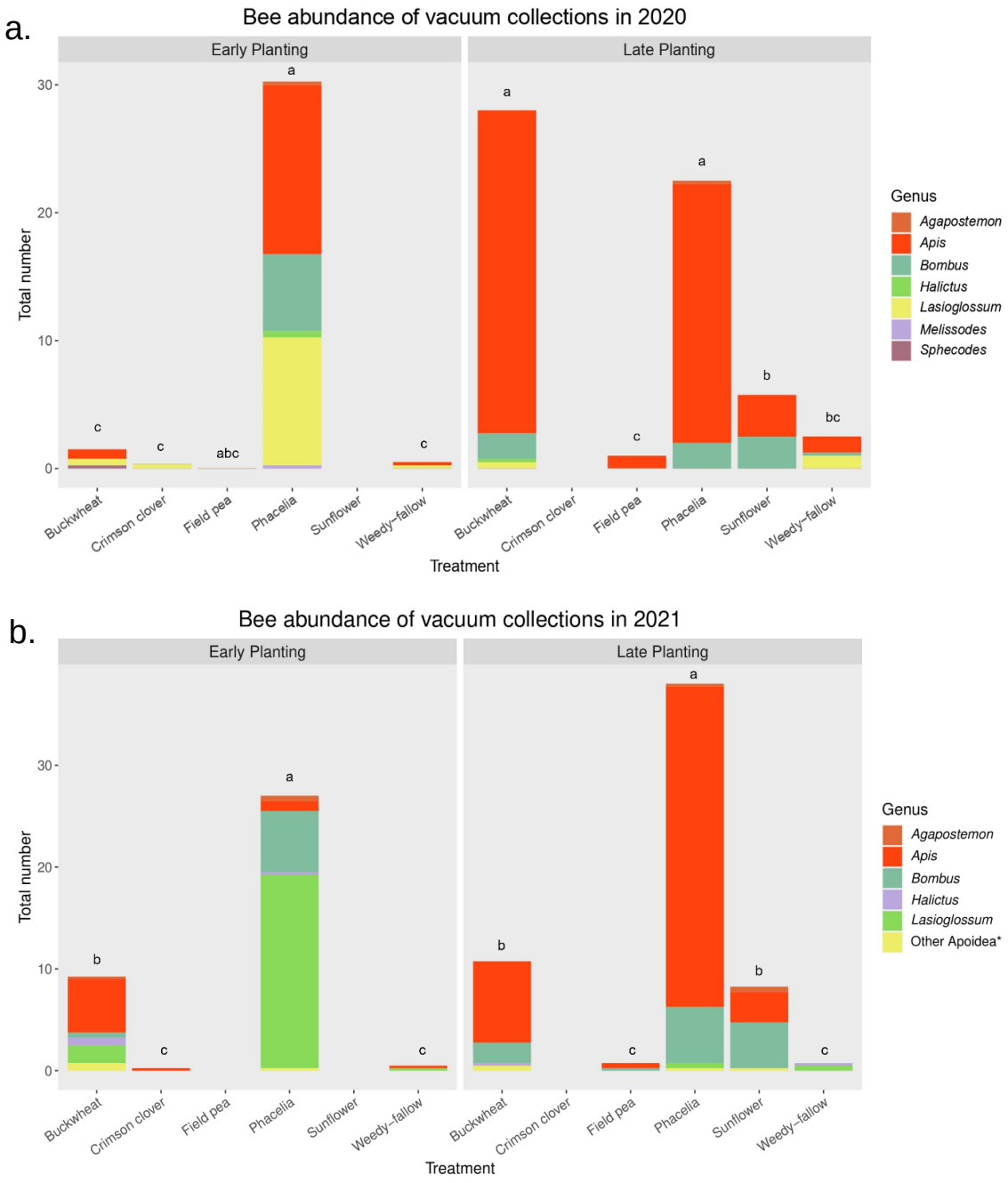

Figure 2a and 2b. Total number of bees by treatment and planting time (Early or Late Planting) of vacuum collections in **a)** 2020 and **b)** 2021. Bee abundance color-coded and represented alphabetically at genus level. **b)** *Genus with low data count were grouped in Other Apoidea. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

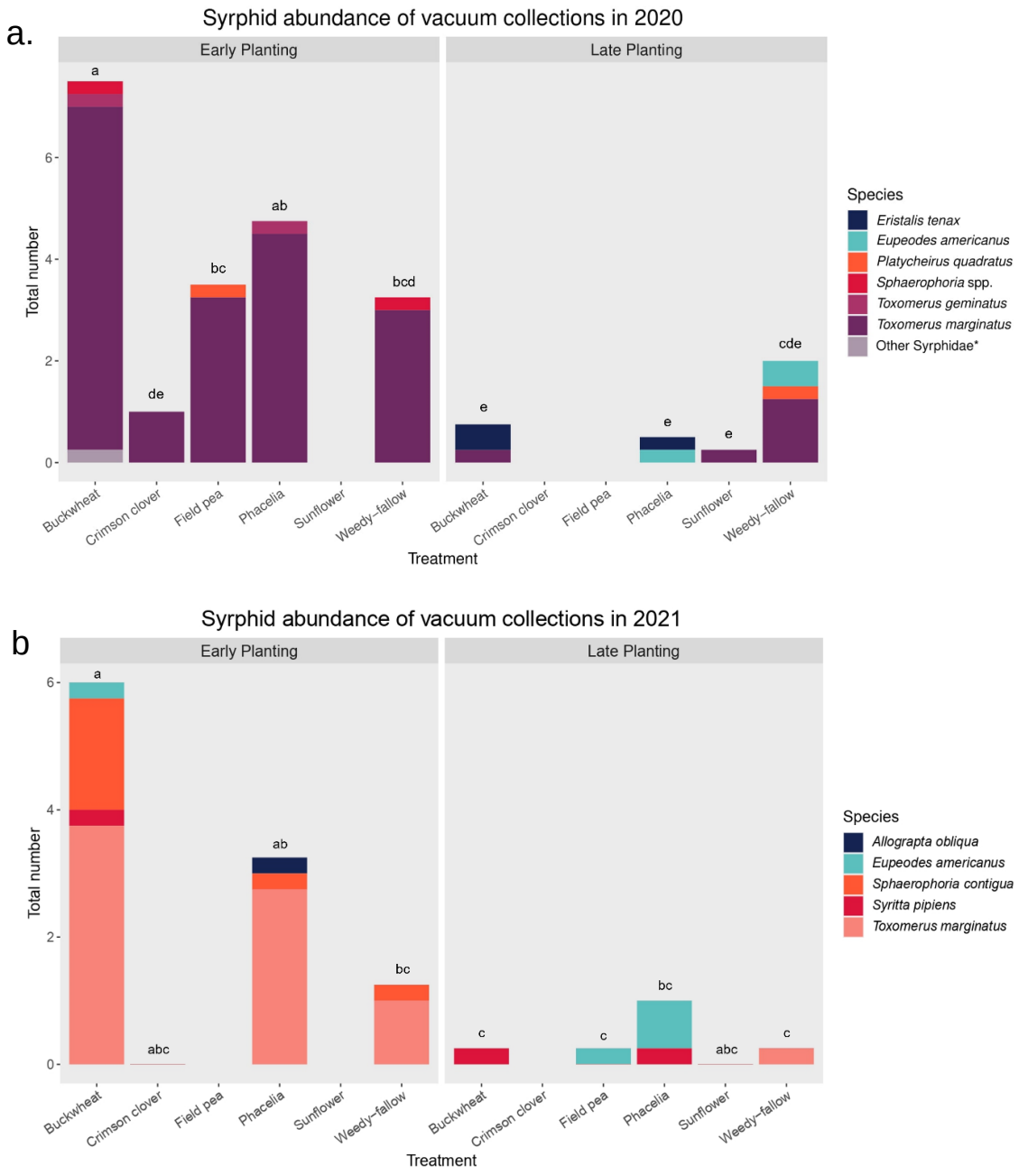

Figure 3a and 3b. Total number of syrphids by treatment and planting time (Early or Late Planting) of vacuum collections in **a)** 2020 and **b)** 2021. Syrphid abundance color-coded and represented alphabetically at species level. **a)** *Species with low data count were grouped in Other Syrphidae. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

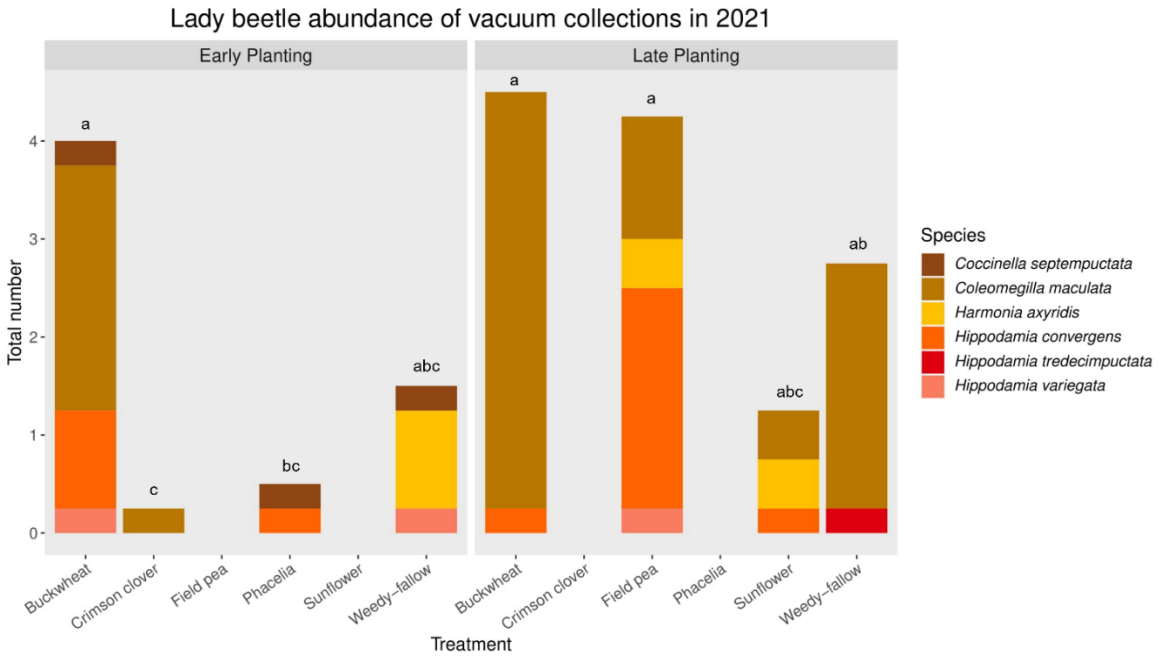

Figure 4. Total number of lady beetles by treatment and planting time (Early or Late Planting) of vacuum collections in 2021. Lady beetle abundance color-coded and represented alphabetically at species level. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

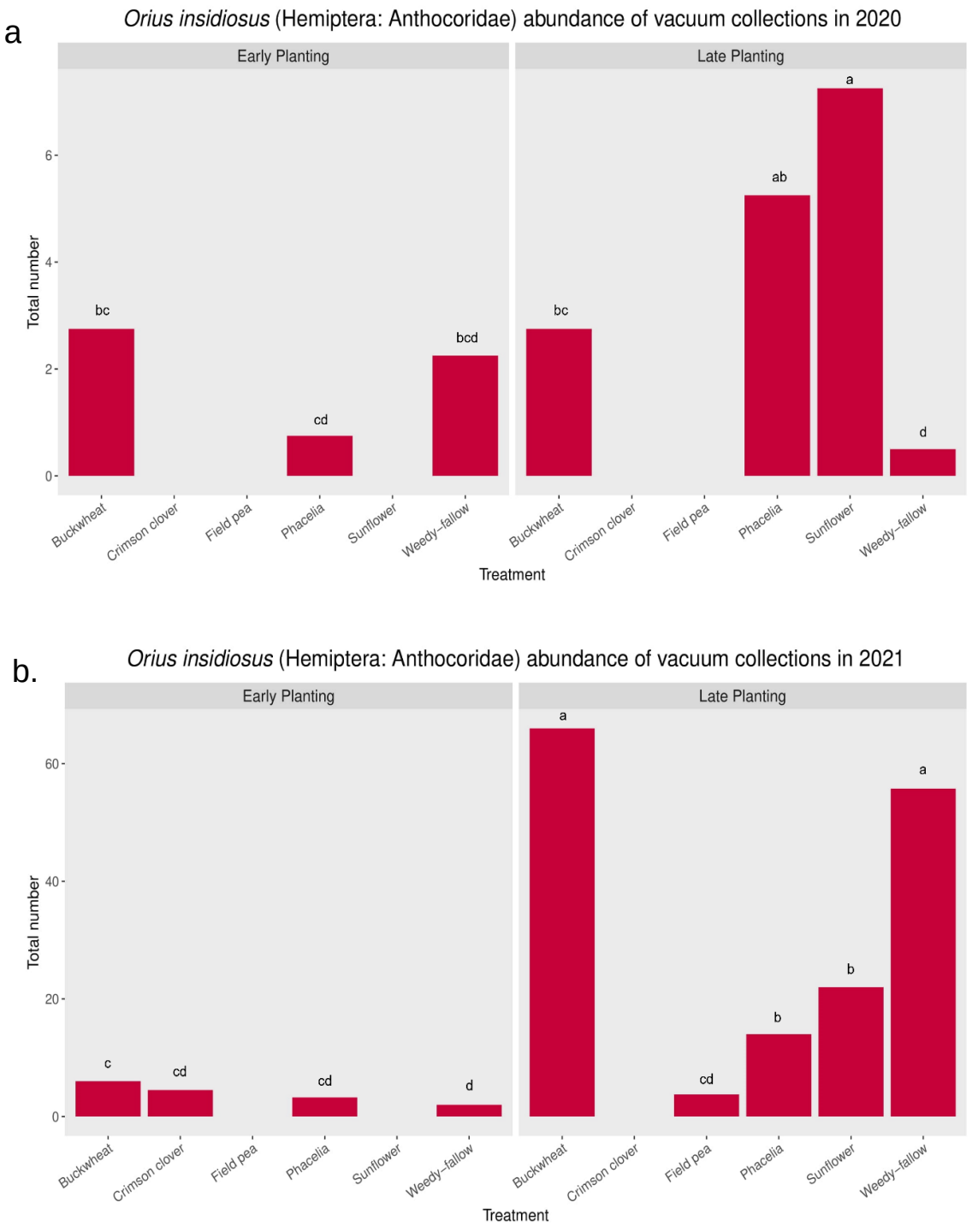

Figure 5a and 5b. Total number of *Orius insidiosus* (family: Anthocoridae) by treatment and planting time (Early or Late Planting) of vacuum collections in **a)** 2020 and **b)** 2021. Anthocoridae abundance in Minnesota represented solely by this species. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

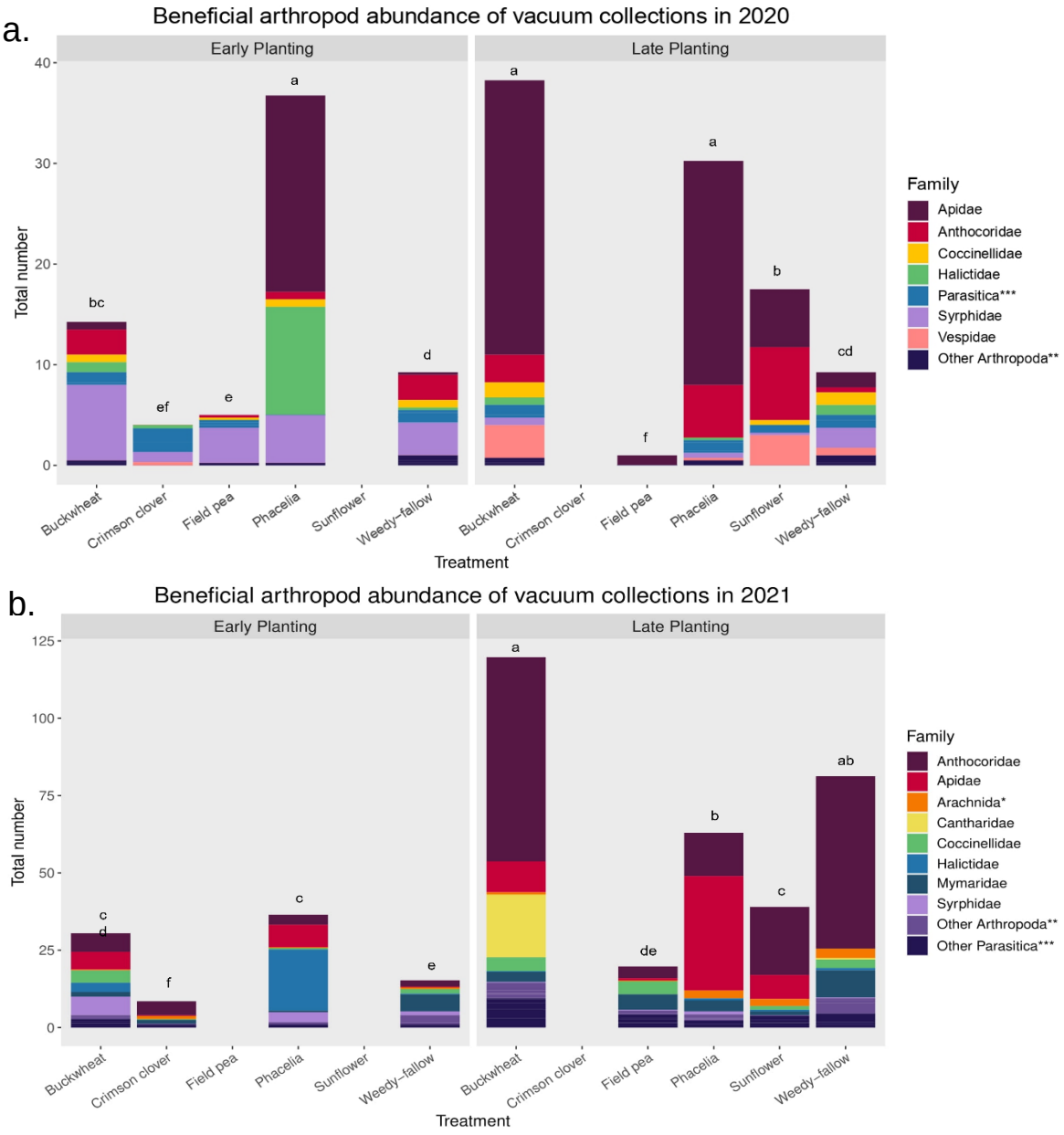

Figure 6a and 6b. Total number of beneficial arthropods by treatment and planting time (Early or Late Planting) of vacuum collections at StP in **a)** 2020 and **b)** 2021. Beneficial arthropod abundance color-coded and represented by functional groups (i.e. bee pollinators, predators, and parasitoids), including phylum**, class*, superfamily***, and family level. **Non parasitic families with low data count were grouped in Other Arthropoda. ***Parasitic families with low data count were grouped in Other Parasitica. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

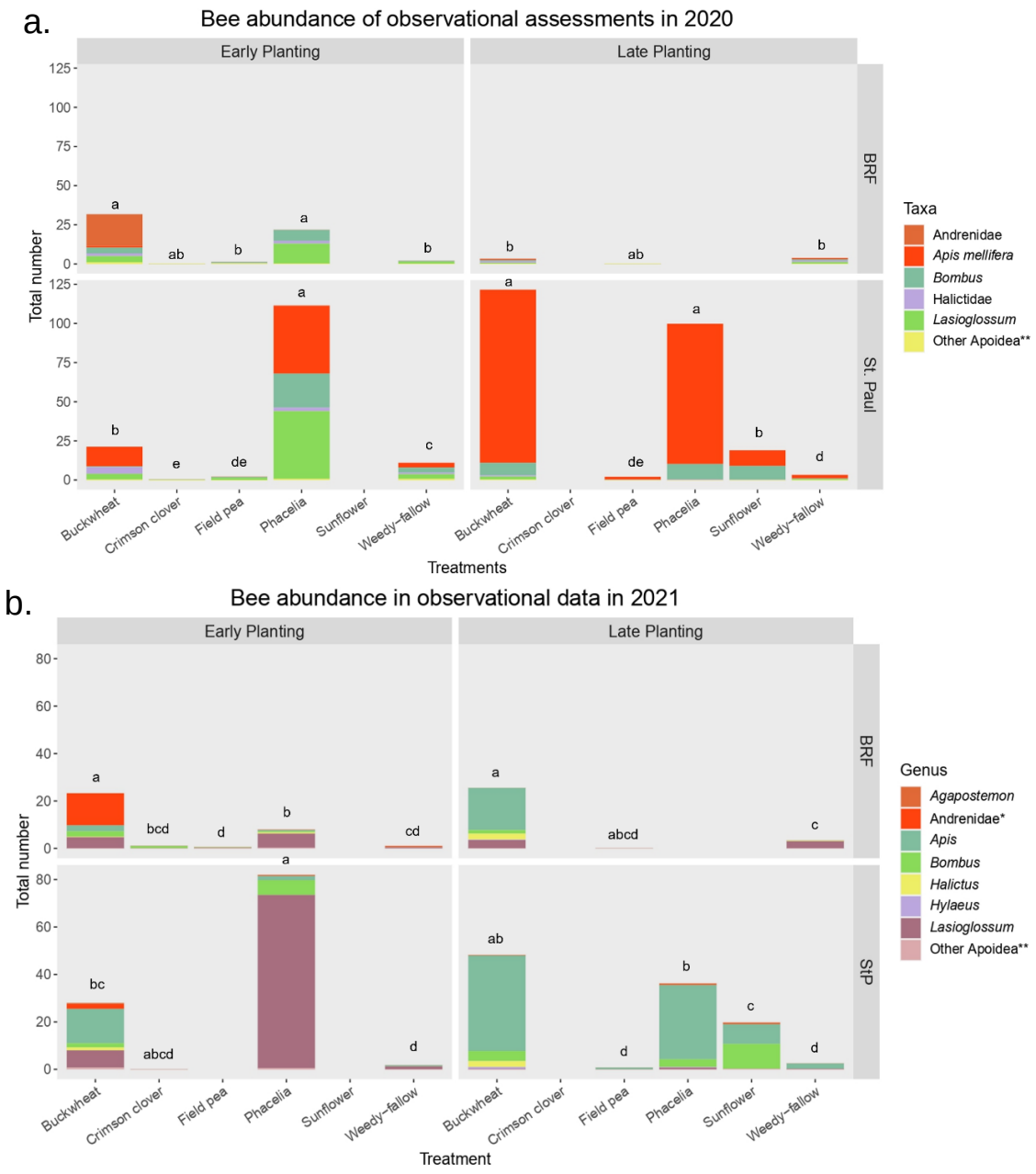

Figure 7a and 7b. Total number of bees by treatment, planting time (Early or Late Planting), and location (BRF and StP) of observational assessments in **a)** 2020 and **b)** 2021. Bee abundance color-coded and represented alphabetically by taxa, including superfamily**, family*, genus (in italic), and species (in italic) level. **Taxa with low data count or unclassified bees were grouped in Other Apoidea. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

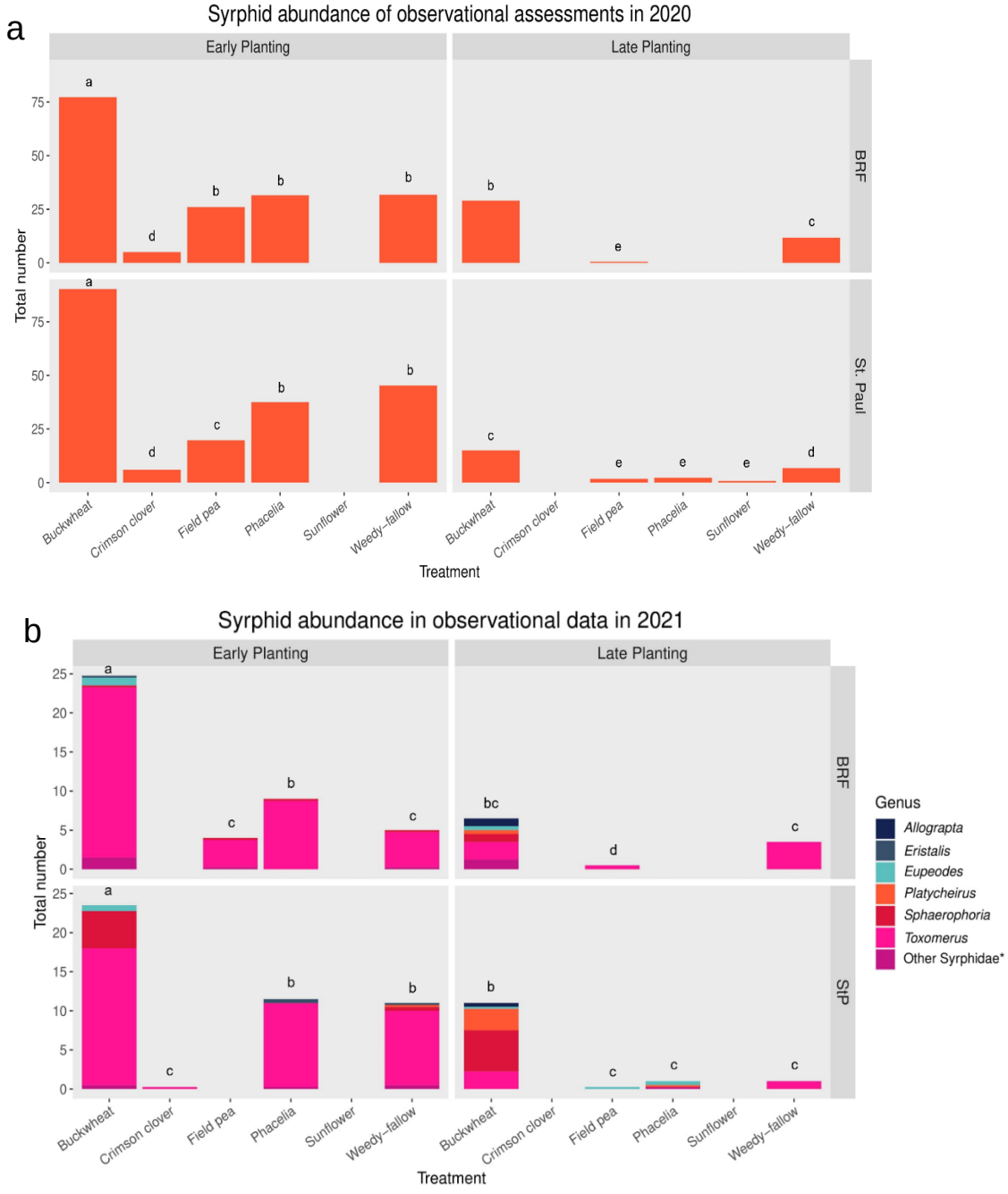

Figure 8a and 8b. Total number of syrphids by treatment, planting time (Early or Late Planting) and location (BRF or StP) of observational assessments in **(a)** 2020 and **(b)** 2021. Syrphid abundance color-coded and represented at **(a)** family and **(b)** genus level. *Genus with low data count or unclassified were grouped in Other Syrphidae. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

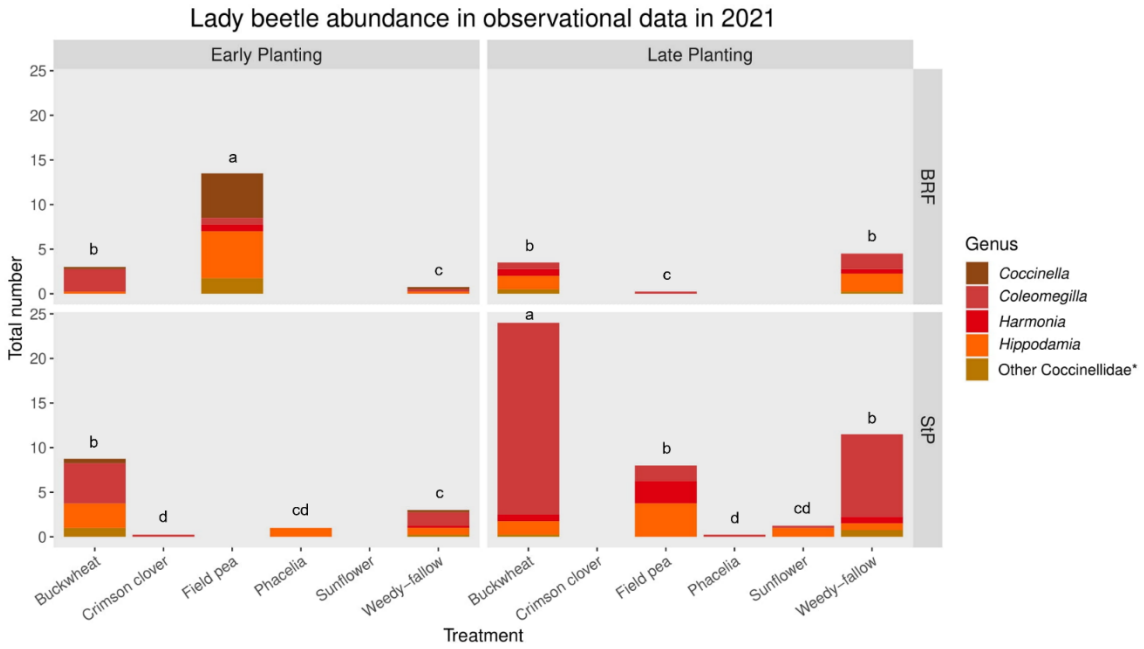

Figure 9. Total number of lady beetles by treatment, planting time (Early or Late Planting), and location (BRF and StP) of observational assessments in 2021. Lady beetle abundance color-coded and represented alphabetically at genus level. *Genus with low data count or unclassified were grouped in Other Coccinellidae. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

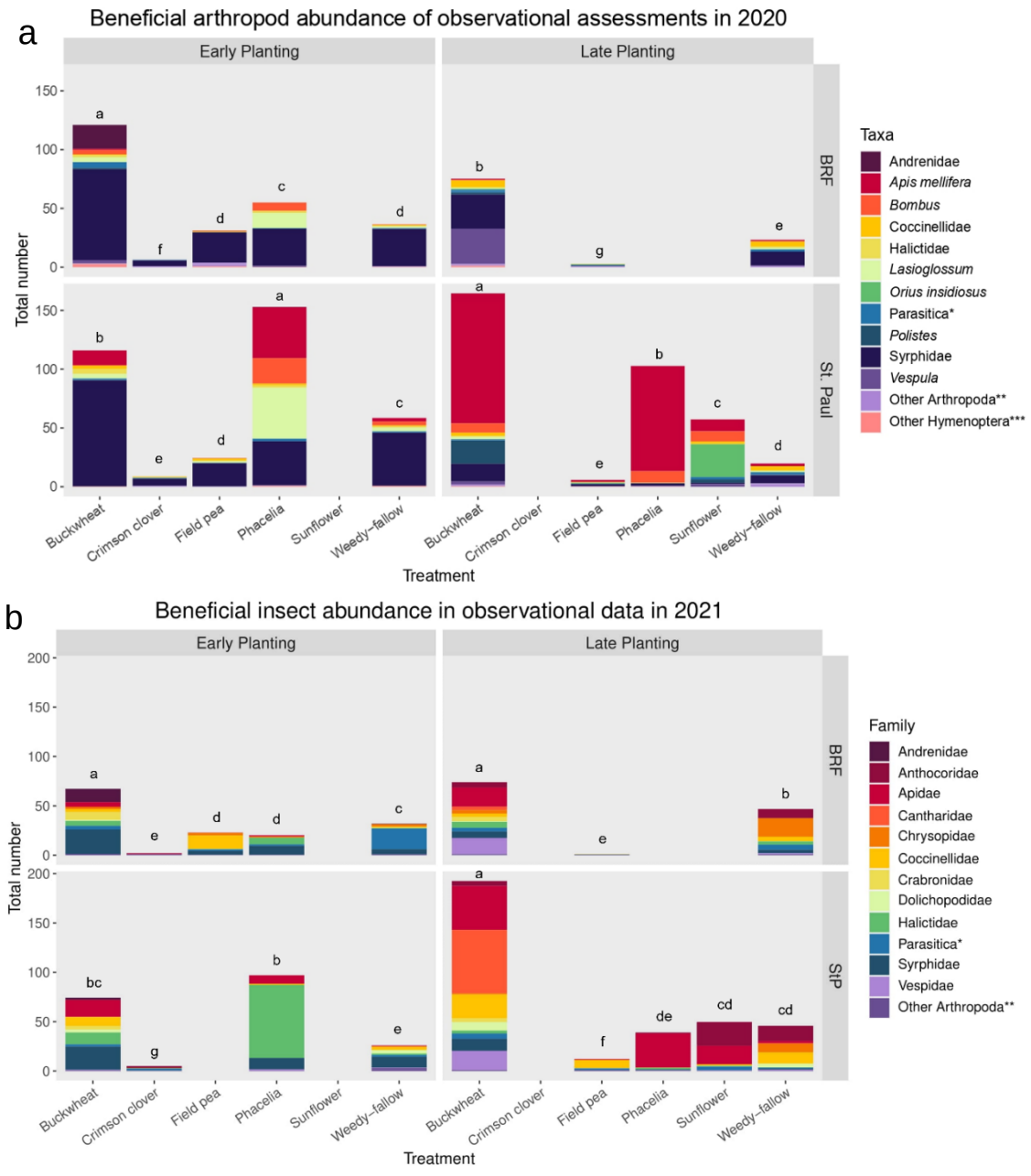

Figure 10a and 10b. Total number of beneficial arthropods by treatment, planting time (Early or Late Planting), and location (BRF or StP) of observational assessments in **(a)** 2020 and **(b)** 2021. Beneficial arthropod abundance color-coded and represented alphabetically by taxa functional group (i.e., bee pollinators, predators, and parasitoids), including phylum**, order***, superfamily*, family, genus (in italic), and species (in italic) level. **Non Hymenoptera specimens with low data count or unclassified were grouped in Other Arthropoda. ***Hymenoptera specimens with low data count were grouped in Other Hymenoptera. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without did not flower and were excluded from the analysis.

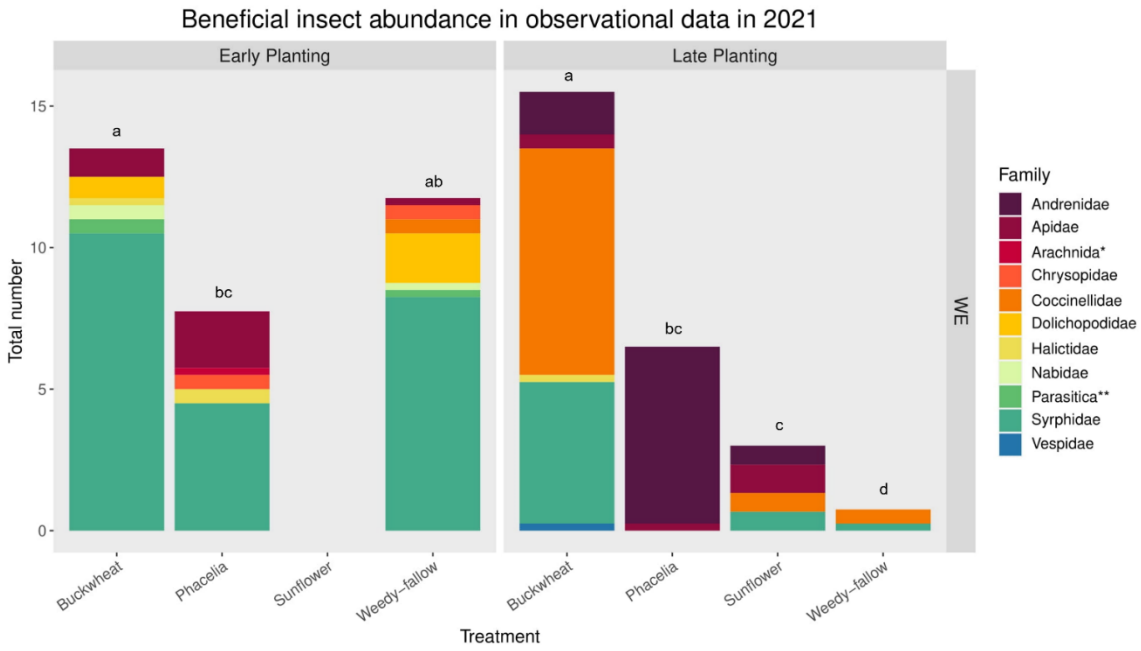

Figure 11. Total number of beneficial arthropods by treatment and planting time (Early or Late Planting) of observational assessments at White Earth (WE) in 2021. Beneficial arthropod abundance color-coded and represented alphabetically by taxa functional group (i.e., bee pollinators, predators, and parasitoids) at class*, superfamily**, and family level. Different letters over columns denote statistically different means at $P \leq 0.05$. Treatments without letters did not flower and were excluded from the analysis.

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