Integrating cover crops in high tunnel production systems

by

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Abstract

The use of high tunnel systems for vegetable crop production is increasing throughout the Central United States. High tunnels provide environmental protection, season extension, increased crop quality and yield, and pest and disease exclusion. In contrast to greenhouse production, high tunnel production is typically soil-based. Intensive cultivation and/or reduced crop rotation intervals that occur in high tunnels and can lead to degradation of soil health. Therefore, this study identified were to identify summer and winter cover crop species could be viable for high tunnel systems and determine their impact on soil properties and arthropod abundance. High tunnel experiments were conducted in 2018 and 2019. There were eight cover crop treatments planted in each season, which included grass, cereal, and legume combinations as well as a weed-free control. Hairy vetch *(Vicia villosa)* and cowpea (*Vigna unguiculata)* were the legume crops planted in the winter and summer experiments, respectively. In the winter experiments, cereal rye (*Secale cereal*) and hairy vetch treatment resulted in the highest biomass yields and cover crop nitrogen contribution *($P < 0.05$)*. In the summer experiment, summer cover crop available N (lbs/acre) was highest for the sorghum-sudangrass treatment (*Sorghum x drummondi)* averaging 100 lbs/acre *($P < 0.05$)* in both years. Increases in soil total carbon (STC), organic matter (OM), and soil total nitrogen (STN) indicated positive effects of cover cropping on soil properties in both seasons. Finally, mites were the dominant soil arthropods recovered in the study and an increase in soil total carbon resulted in higher mite numbers in the summer experiment. Soil organic matter influenced the abundance of mites differently in the two seasons. In the summer experiment, an increase in percent organic matter after termination was associated with an increase in mite abundance. However, in the winter experiment, higher organic matter was associated with lower mite numbers. In the summer experiment, mite abundance was higher

in buckwheat and cowpea cover crop treatments than the other treatments. A mean of 0.82 mites per 96 g of soil were recovered in 2018 and 2019 from the buckwheat and cowpea treatment, whereas in the control treatment an average of 0.02 mites were recovered in the summer experiments. Soil moisture and soil total nitrogen did not have an effect on mite abundance in the study. Therefore, in this study cover crop rotations in high tunnels unveiled associated trends in soil properties and arthropod abundance.

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Dedication

Land that drinks in the rain often falling on it, and that produces a crop useful to those for whom it is farmed receives the blessing of God.

-Hebrews 6:7

Chapter 1- Literature Review

Food Production in High Tunnel Cropping Systems

High tunnels are semi-permanent, moveable, or temporary structures that are constructed with a metal, wooden, or polyvinylchloride (PVC) frame and a plastic film covering (Knewtson et al., 2012; Carey et al., 2009). Typically, high tunnels are passively heated and cooled and crops are grown directly in the soil (Bruce et al., 2017). High tunnels were initially considered to have been developed in the United States but were adopted early by growers in Europe and Asia (Carey et al., 2009; Knewston et al., 2012). Research in the 1990's associated with these structures for vegetable crop production increased for warm-season crops such as tomato (*Solanum lycopersicum*) (Carey et al., 2009). While the use of plastic covered growing systems began in the 1950s, knowledge of their potential benefits increased in nursery production, and later small fruit and vegetable production systems (Knewtson et al., 2012).

High tunnels are an expensive investment due to the material, installation, and maintenance costs (Waterer, 2003) compared to open field (Sydorovych et al., 2013). Research on the costs and benefits of high tunnel production indicate that initial investment costs can be recovered within the first two years of horticultural production (Carey et al., 2009; Sydorovych et al., 2013). However, this depends on crop selection and local environmental conditions (Carey et al., 2009).

High tunnels are heated by solar radiation and cooled by passive ventilation (Knewtson et al., 2012; Carey et al., 2009). High tunnel ventilation involves rolling up the plastic on the side walls and end walls of the tunnel (Waterer, 2003). Polyethylene film is typically removed from multi-span high tunnels in areas where snow and ice accumulate during the winter (Carey et al., 2009). The soil in high tunnels is typically tilled at the end of each growing season and crop residues are removed prior to planting the subsequent cash crop (Waterer, 2003). Innovations in agricultural production practices and structures have been expanding rapidly during the past century (Wittwer and Castilla, 1995). Field production, primarily climate- and weather-dependent, was the primary method of horticultural production before the advent of high tunnel technology. “The most determinant factor in horticultural crop production is the climate” (Wittwer and Castilla, 1995). Lack of sunlight, temperatures that are too hot or cold, moisture deficiencies or excesses, and excessive wind velocity are some constraints in horticultural crop production. However, many of these constraints are lessened by protected cultivation or controlled growing environments (Wittwer and Castilla, 1995).

One of the most important benefits of high tunnel production is the microclimate(Lamont, 2009), which allows for year-round crop production in some climates (Lamont, 2009). In temperate regions, high tunnels allow for an extended growing season by warming the air and soil (Lamont, 2009). The increased soil warming in spring and cooling in the fall make the high tunnel microclimate favorable for farmers (Lamont, 2009). In tropical areas, high tunnels reduce the impacts of harsh weather conditions (monsoon winds, rain, etc.) on crop production, while also extending the growing season (Lamont, 2009). In tropical areas, high tunnels are often covered with shade cloth or insect screening and not polyethylene film. Protected cultivation enables growers to mitigate wind velocity, temperature, light intensity, and moisture (Bruce et al., 2017; Wittwer and Castilla, 1995). High tunnel covers can diffuse sunlight, enhancing light penetration into the canopy, allowing uniform light distribution on foliage and increased photosynthesis during production (Kadir et al., 2006).

High tunnels allow for the production of high value crops earlier in the season than field-grown crops (Kadir et al., 2006; Rader and Karlsson, 2006). Survey data collected at farmer’s markets in Michigan showed that consumers are willing to pay higher prices for tomatoes and other vegetables late and early in the season (Conner et al., 2009). While vegetable production is more common than fruit production in high tunnels, the benefit of the extended season makes small fruit production viable in high tunnels (Lamont, 2009). Crops typically grown in high tunnels include: tomato, sweet pepper (*Capsicum annuum* Grossum group), and cucumber (*Cucumis sativus*) (Lamont, 2009). Tomato is a noteworthy high tunnel crop because tomatoes grown in high tunnels are of higher quality generally and ready to market earlier than open-field tomatoes (Carey et al., 2009). Early maturity can be due to increased heat, raising air and/or soil temperatures—which promotes root growth and reduces the negative effects of low nighttime temperatures (Kadir et al., 2006).

Impact of High Tunnel Production on Food Systems

The adoption of high tunnel production in the U.S. benefited the farmer and consumer. Farmers benefit because they can be used to produce high quality, high-value horticultural crops (Foust-Meyer and O'Rourke, 2015). There is a high demand for fresh vegetables in domestic and export markets throughout the year (Lodhi et al., 2013; Norris and Congreves, 2018). The supply of fresh vegetables is often limited due to seasonal climatic variations (Lodhi et al., 2013). In-season, markets are flooded with low-priced, fresh vegetables; in the off-season, consumer's local options are limited to high-priced vegetables (Lodhi et al., 2013). High tunnel crop production is a technology that can help growers produce vegetables during the off-season (Lodhi et al., 2013). With increasing demand for food from local markets, high tunnel production is increasing opportunities for local food production world-wide (Foust-Meyer and O'Rourke, 2015; Meyer, 2016).

Food insecurity is on the rise globally due to the volatility in global markets and food supply (Foust-Meyer and O'Rourke, 2015). Increasing local food production has been offered as one option to boost food security and combat the ill effects of globalization (Foust-Meyer and O'Rourke, 2015). For many farmers, selling vegetables locally offers a valuable market diversification strategy, meeting consumer demand for the "local" attribute, while increasing their portion of the consumer food dollar (Conner, 2009). Between 1992 and 2007, local food production increased exponentially, increasing direct-to-consumer sales (Foust-Meyer and O'Rourke, 2015). In order to help bolster these efforts, the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) began subsidizing the purchase of high tunnels in 2010 (Foust-Meyer and O'Rourke, 2015). Then deputy-secretary of the NRCS explained that subsidized high tunnels served as a means to improve food production in climates that would not be possible otherwise (Foust-Meyer and O'Rourke, 2015). Also, the deputy-secretary shared that "farmers who sell their high tunnel produce locally benefit from the extra income and the community benefits from the availability of fresh, locally grown food" (Foust-Meyer and O'Rourke, 2015).

Production Practices in High Tunnel Systems

Despite the many benefits of high tunnel crop production there are costs to long-term soil management. To meet the demands of the market, farmers typically manage high tunnels intensively, leading to soil degradation (Norris and Congreves, 2018). Intense cultivation can lead to gradual declines in soil fertility and lower productivity (Brown, 1983).

According to the Food and Agriculture Organization of the United Nations, global vegetable production is increasing due to national health guidelines that encourage vegetable consumption (Norris and Congreves, 2018). "However, due to vegetable crop growth requirements and their perishable nature, soils under vegetable crop production are managed extremely intensively…" (Norris and Congreves, 2018). Due to concerns of global environmental impacts from land clearing to loss of biodiversity in agriculture, intensive production has caused global food demands to be met with environmental trade-offs (Tilman et al., 2011).

About a quarter of greenhouse gas emissions are a result of crop production and fertilization practices (Tilman et al., 2011). It is predicted that increased intensification of agricultural production to meet global food demands will inevitably be accompanied by increased soil erosion, loss of fertility, decreases in soil biomass, and biodiversity (biota) (Babin et al., 2019; Pereira et al., 2018). Also, there could be an accumulation of agro-chemicals and phytopathogens if sustainable practices are not adopted globally (Babin et al., 2019; Pereira et al., 2018).

The value of soil in the agroecosystem is often measured by the ecosystem services it provides (Pereira et al., 2018). In an agricultural system, some of these services may include conservation and accumulation of carbon, water, and nutrients. Healthy soils are able to regulate these processes as well as regulate greenhouse gas emissions and promote resistance to diseases and pests (Pereira et al., 2018). Soil management practices affect the quantity and quality of the ecosystem services provided by soils. In intensive production systems, soil ecosystem services are rapidly degraded (Pereira et al., 2018).

Some intensive production practices that negatively affect soil ecosystem services include short crop rotations, over-use of fertilizers, and conventional tillage (Pereira et al., 2018). High tunnel growers typically till after each cropping cycle, thus removing crop residues before planting a subsequent cash crop (Waterer, 2003). This practice can be repeated multiple times per year (Lamont, 2009). However, intensive tillage destroys the natural soil structure resulting in a soil with reduced production capacity and ability to accommodate soil fauna (Parvatha Reddy, 2016). While tillage helps loosen the soil in preparation for a smoother seedbed, crop residues are buried, resulting in dry soils, which promotes soil erosion (Parvatha Reddy, 2016). Soil erosion in agricultural systems can be caused by water, wind, of through intensive farming practices such as tillage (Ritter, 2012). In tillage erosion, soil is redistributed through tillage and gravity. Erosion may not seem possible in a high tunnel system, however, intensive tillage can cause soil loss due to progressively down-slope movement of soil (Poesen et al., 1997; Ritter, 2012). This intensive production can reduce the long-term vitality and capacity of soils (Pereira et al., 2018).

Production Practices and Soil Health

Soil is vital to the function of terrestrial ecosystems (Pankhurst et al., 1997), and is a relatively non-renewable resource; taking 100 to 400 years to form a centimeter of topsoil. In general, soil health is "the ability of soil to perform or function according to its potential, and changes over time due to human use and management or to natural events" (Pankhurst et al., 1997). Soil health is often difficult to measure and interpret since it depends on various soil functions and uses across ecosystems and agricultural production sites (Norris and Congreves, 2018; Pankhurst et al., 1997). Most studies focused on improving crop production while minimizing the negative effects on soil health and the ecosystem are not focused on vegetable production, but on field crops, with 70% of the crops used for animal feed (Norris and Congreves, 2018). This has created a research gap in both open field vegetable crop production and high tunnel production that must be addressed as intensive production in vegetable production systems is common (Norris and Congreves, 2018).

Soil Chemical Properties

Topsoil is a critical resource in food production that can be easily lost, resulting in the subsoil becoming part of the tillage layer. Topsoil is nutrient rich, containing the needed soil organic matter for food production along with other structural properties (water holding capacity, aeration) for ideal plant growth (Brown, 1983). In light of the functions of topsoil, sustainable food production should focus on increasing soil quality rather than expanding cropland (Brown, 1983). Despite the various functions of topsoil, soil management practices for vegetable crop production is typically intensive, utilizing more fertilizers than required (Campiglia et al., 2010). There are multiple reasons for the increased use of fertilizers in high tunnel systems such as: (1) high nutrient demand of vegetable crops (2) economic value of increased yields (3) farmer's gap in knowledge of fertilizer and irrigation water best practices (Congreves and Norris, 2018; Ju et al., 2007).

In a study conducted in Northern China, the effects of high fertilizer inputs in greenhouses were assessed (Ju et al., 2007). It was found that high fertilizer input coupled with low living plant cover lead to soil and groundwater degradation (Tonitto et al., 2006) and an accumulation of phosphorus with marked imbalances of N, P, and K for optimal vegetable crop production (Ju et al., 2007). More recently, protected vegetable cropping systems research has seen similar results and management practices can significantly affect soil chemical properties (Ge et al., 2011; Meyer, 2016). In conventionally managed production systems, soil pH is higher, soil salinity is increased, and total organic carbon and total N is less than in organically managed systems (Ge et al., 2011). These changes in soil chemical properties can accompany changes in belowground arthropod activity including soil aggregate stability, and nutrient cycling (Haynes and Tregurtha, 1997). The most significant change is in soil organic carbon and organic matter (Haynes and Tregurtha, 1997).

Soil is one of the largest global pools of organic carbon, containing three to four times the amount of carbon found in the atmosphere or plant tissues (Hamilton et al., 2015). Soil studies utilize the terms "organic matter" and "soil organic carbon" to express trends in soil carbon reserves with particulate organic matter carbon as an ideal indicator of soil quality (Brady and Weil, 2004; Knewston, 2008). Soil organic matter consists of plant, animal, and microorganism remains that have been broken down by other microorganisms. As organic matter is formed in the soils, carbon may be lost through microbial respiration in the form of carbon dioxide (Brady and Weil, 2004). Despite soil organic matter being only a small fraction of soil (1-6% of total volume in most agricultural soils), it is vital to food production (Hamilton et al., 2015). Organic matter aids in soil aggregation (providing structural support for plant roots) and water holding capacity (storage and movement of water available for plants) for proper plant growth (Brady and Weil, 2004; Hamilton et al., 2015).

There are three main divisions of soil organic matter as expressed in Brady and Weil (2004). These fractions include active soil organic matter, passive organic matter, and slow organic matter. The active fraction is identified as the fraction with the highest carbon to nitrogen ratio and can be quickly metabolized (Brady and Weil, 2004). This fraction is the most essential portion since it provides food for soil organisms and provides mineralizable nitrogen. Active soil organic matter can be produced in 1-2 years and is largely responsible for soil structural stability (Brady and Weil, 2004). Alterations in climate and management practices can readily affect the active fraction, making it a sensitive component of the overall soil composition (Brady and Weil, 2004). The passive and slow fractions of organic matter occupy 60-90% of soil organic matter with its compositional changes occurring at a slow pace. These fractions of soil organic matter are responsible for storing food for steady metabolism of soil microbes, mineralizable nitrogen and other plant nutrients (Brady and Weil, 2004). In a study looking at how cultivation of natural ecosystems affected active, passive, and slow organic matter percentages, it showed that long-term cultivation practices (40 years), resulted in a 90% decline in active soil organic matter. Whereas, the passive fraction experienced an 11% decline (Brady and Weil, 2004). This study illustrated how cultivation practices affect the most important fraction of soil organic matter--the active fraction (Brady and Weil, 2004). However, the pendulum of change in the active fraction swings both ways, depending on the management practices employed.

Changes in the upper seven cm of the soil profile due to soil management practices can have profound effects on soil organic matter accumulation (Hamilton et al., 2015). Studies show that sustainable farming practices can result in slowing or reversing soil carbon losses (Hamilton et al., 2015). Some sustainable practices that have influenced soil organic matter include no-till farming and the use of cover crops on farm (Hamilton et al., 2015). Changes in soil management practices may cause only small changes in total soil organic matter but those small changes have notable effects on soil aggregation, nitrogen mineralization, and other properties (Brady and Weil, 2004). This is because of the sensitivity of the active organic matter fraction to changes (increases or decreases) in overall soil organic matter (Brady and Weil, 2004). Thus, changes in total organic matter percentages can create marked changes in the active fraction (Brady and Weil, 2004).

Climatic factors can also influence changes in soil organic matter. The soil works as an ecosystem resource, aiding in carbon sequestration, and also returning carbon dioxide back to the atmosphere through microbial respiration (Brady and Weil, 2004; Hamilton et al., 2015). In high tunnel systems where sunlight penetration is more uniform, the influence of climate on soil organic matter likely differs from the open-field.

Soil Biological Properties

Arthropods are classified according to their functional groups; some of these groups include shredders, herbivores, predators, and fungal feeders (United States. Natural Resources Conservation Service., 2000). These classifications help in understanding the roles of arthropods in agroecosystems. Consequently, indices of soil species diversity have been used to make inferences about soil ecosystem stability and resilience (Ferris and Tuomisto, 2015). Studies have used free living nematode abundance as an index of soil management practices since they are important players in soil nutrient cycling and are sensitive to land management practices (Leslie et al., 2017). Intensive agricultural practices can result in decreased biodiversity (Langerlof, 1987; Leslie et al., 2017). Belowground arthropods in soils supporting food and fiber production have lower diversity and abundance (Langerlof, 1987).

Monitoring for belowground arthropods for conservation biology research is becoming more popular (Mattoni et al., 2000). Investigations on how agricultural practices may affect the belowground arthropods is also growing (Erb and Lu, 2013; Langerlof, 1987; Mattoni et al., 2000). Belowground arthropods (insects and mites) are sensitive to disturbances and changes in environmental conditions, allowing them to serve as indicators of ecosystem change (Mattoni et al., 2000; Kremen et al., 1993). Trends in belowground arthropod abundance and species diversity in agricultural systems may signal changes in soil conditions and reveal the effects of soil management strategies.

One of the important ecosystem services of soil is the microhabitats it creates for meso- and macro-fauna. A microhabitat as defined by Merriam-Webster (2020) is "the microenvironment in which an organism lives." In the case of soil, soil provides microhabitats for a diversity of organisms of different sizes, activity, and functions (Ferris and Tuomisto, 2015). Some of these organisms are essential to making the provision of food and fiber possible (Pereira et al., 2018). Outside of microorganisms such as bacteria, fungi and protozoa, soil fauna is mainly composed of two groups of microarthropods: collembola and mites (Pereira et al., 2018; Benckiser, 1997). These organisms can be described as ecosystem engineers because of their ability to alter soil physical parameters and stabilize soil through the formation of microaggregates (Benckiser, 1997). Soil fauna such as decomposers, fungal-feeders, and shredders are responsible for transferring energy up the food chain in the soil food web (Price et al., 2011; Pearsons and Tooker, 2017; NRCS, 2000). Arthropods and earthworms are litter transformers that fragment and shred plant residue (Culliney, 2013; NRCS, 2000). That is later decomposed through microbial activity (Culliney, 2013). Belowground arthropods feed on microorganisms (fungi and bacteria) accelerating the release of nutrients into soil in an available form for plant uptake rather than being immobilized in microbial biomass (Langerlof, 1987). By transforming plant residues, promotion of bacterial and fungal colonization, and energy recycling, many belowground arthropods such as Collembola, Oribatida, Myriapoda, and Isopoda promote the growth and maintenance of the soil microbiome (Culliney, 2013; Price et al., 2011).

Soil arthropods can also reduce weed pressure through physical and biological means (Shearin et al., 2008). For example, ground-dwelling arthropods consume post-dispersal seeds (Shearin et al., 2008). Cromar et al. (1999) found that these arthropods can consume 80 to 90%

of lambsquarter (*Chenopodium album*) and barnyard grass (*Echinochloa crus-galli (L.) Beauv*.) seeds (Cromar et al., 1999; Shearin et al., 2008). Belowground arthropods may also improve soil aeration and consumption of other organisms (fungi, earthworms, and other arthropods) (NRCS, 2000).

As discussed earlier, intensive management practices can have a negative effect on soil properties. Intensive agriculture practices such as intensive tillage, frequent crop rotations, and increased fertilization can affect belowground arthropod abundance and diversity (Benckiser, 1997). The effect of intensive tillage on arthropod communities is due to physical displacement of mesofauna and plant residues after tilling, and changes in soil moisture as well as reducing microbial growth conditions (Benckiser, 1997). Studies conducted by Bund (1970) revealed that intensive tillage had a negative effect on the diversity of species of mites and springtails found in agricultural soils, but not on the numbers of thee arthropods (Benckiser, 1997; Bund, 1970). Long-term tillage increased the abundance of springtails and mites in the upper 5 to 15 cm of soil (Benckiser, 1997). However other studies have found increases in arthropods by about 350% in no-till plots versus tilled plots (Edwards and Lofty, 1977; Benckiser, 1997). In a long-term study, it was found that arthropod populations declined after 35 years of intensive agricultural practices (Shearin et al., 2008). Intensive practices can profoundly influence soil compaction and bulk density (Allen and Musick, 1997; Shah et al., 2017). In a 2013 report, root herbivore larvae displayed marked changes in mobility due to soil bulk density and soil type (Erb and Lu, 2013). As bulk density increased, arthropod mobility decreased (Erb and Lu, 2013). In soils where arthropods were immobilized, they were not able to access nutrients leading to premature death and decreases in arthropod diversity and abundance (Erb and Lu, 2013; Pacchioli and Hower, 2004).

Crop rotations can affect plant-insect interactions either negatively or positively (Benckiser, 1997). Springtails can prefer wheat and barley crops as a food source, resulting in increased abundance, whereas, abundance is lower under sugar beet and other root and tuber crops (Benckiser, 1997). Tilling cover crop residues back into the soil may result in a high abundance of arthropod species even in winter (Benckiser, 1997).

The effects of increased fertilization in agricultural systems on belowground arthropods is unclear. Springtails have been found to survive in systems where high amounts of fertilizer are followed by plant residue cover (Benckiser, 1997). Similarly, mite abundance has been found to increase due to increased fertilization (Benckiser, 1997). In a study evaluating root-herbivore interactions, increased fertilization increased *Lissorhoptrus oryzophilus* abundance in rice production systems (Erb and Lu, 2013). However, these results may not be common, and may be due to modifications in these organisms' diets based on other agricultural management practices, regional climatic conditions, and soil types (Benckiser, 1997). Also, changes in soil nutrients may trigger chemical root defense responses that can affect belowground arthropod abundance (Erb and Lu, 2013).

Abiotic soil conditions can affect the abundance of belowground arthropods (Erb and Lu, 2013). Water is present in soil in the form of solid, liquid, and gas and affects belowground arthropod assemblages (Villani and Wright, 1990). For example, in dry soils root feeders migrate deeper in the soil profile to escape dry conditions (Erb and Lu, 2013). In field studies, early drought conditions resulted in significantly fewer root herbivores (Erb and Lu, 2013). However, once herbivores have established on root tissues they are less sensitive to drought stress because they obtain moisture from the roots (Erb and Lu, 2013). Although, dry conditions can significantly affect belowground arthropod mortality, excessive soil moisture can have the same effect. Excessive soil moisture negatively affects belowground arthropod abundance by creating an anoxic soil environment (Erb and Lu, 2013; Eskafi and Fernandez, 1990).

Studies have shown that soil nutrient availability does not impact the abundance of belowground arthropods, as some arthropods such as root feeders derive their nutrients from plant roots (Erb and Lu, 2013). However, root feeders' reliance on plant tissues for nutrients makes them indirectly dependent on soil nutrients for growth and development (Erb and Lu, 2013). Therefore, root feeders and non-root feeders alike can be affected by soil nutrients either directly or indirectly. Organic matter specifically affects the bioavailability of soil nutrients by improving microbial activity (Erb and Lu, 2013). The addition of cover crop residues in agricultural systems helps promote microbial activity and decomposition of organic material (Duval et al., 2016). Cover cropping can provide organic matter for crop production, diversify arthropod communities, and increase arthropod abundance compared to conventional practices (Buchanan and Hooks, 2018).

Cover cropping in Intensive Production Systems

Cover cropping has been used for centuries in agricultural systems to decrease erosion, increase soil health, and suppress weeds (Campiglia et al., 2010; Leslie et al., 2017). Some cover crops are used for soil nitrogen management (decreasing N leaching) while others are used for a green manure effect (increasing soil organic matter and nutrient content) (Tribouillois et al., 2016). Non-leguminous cover crops are generally high biomass yielding plants (having higher C:N ratios) while leguminous (N-fixing) cover crops like hairy vetch or cowpea, are able to increase the soil N content by fixing atmospheric nitrogen into a usable form of nitrogen for cash crop production (Kim et al., 2013; Belfry et al., 2017). In agricultural systems, barley (*Hordeum vulgare*) has been used to suppress weeds through allelopathy (Leslie et al., 2017).

The use of cover crops around the world is increasing as the urgency of using sustainable farming practices and environmental stewardship is growing (Leslie et al., 2017). Intensive production practices used globally to increase food production has been accompanied by environmental pollution and an overuse of fertilizers (Campiglia et al., 2010). As environmental awareness grows, the demand for low-input food production is increasing. Alternative field practices are also in demand due to the rapid depletion of natural resources (petroleum), encouraging farmers to invest in different technologies such as no-till and cover cropping (Campiglia et al., 2010).

Cover crop functions are dependent on the cover crop species, the amount of cover crop residue, and cover crop management practices (Leslie et al., 2017). Species selection is imperative as each cover crop can provide different nutrients to the growing system and have different root growth patterns (Leslie et al., 2017). Many growers mix cover crop species to achieve the desired soil management results. Research shows that growing leguminous species with non-leguminous species can maximize the benefits of each species based on the principle of niche complementarity (Jensen, 1996; Tribouillois et al., 2016). Proper cover crop mixture selection can aid in reducing the C:N ratio to promote N release for subsequent cash crop growth and avoid N immobilization in the soil (which occurs when non-leguminous cover crops are grown exclusively) (Tribouillois et al., 2016). Studies have shown that legumes fix more N when grown with cereal species (Jensen, 1996; Tribouillois et al., 2016). Cover crop species and mixture performance is dependent on the site’s soil, climatic conditions, and soil management practices (Tribouillois et al., 2016).

Cover crops that have been recommended in vegetable crop production can be grown alone or in mixtures (Barel et al., 2018). Field studies investigating the performance of winter cover crops found non-leguminous species typically outperform legumes in aboveground and belowground biomass yields (Barel et al., 2018). Winter legumes such as hairy vetch, may have low root biomass compared to non-leguminous species, but can have twice as much nitrogen concentration than non-legumes due to their ability to fix nitrogen (Barel et al., 2018). Nitrogen fixation has a profound effect on increasing potential soil nitrogen reserves (Barel et al., 2018). Legume biomass nitrogen increases as the crop's biomass increases (Creamer and Baldwin, 2000). Research on cowpea development shows that nitrogen in cowpea tissues can double between weeks 5 and 7 (Franzluebbers et al., 1994). Non-leguminous crops such as rye (*Secale cereale*), sorghum-sudangrass (*Sorghum x drummondi*), and buckwheat (*Fagopyrum esculentum*) are recommended for their ability to aid in weed suppression, increase soil organic matter, and soil nitrogen management (Creamer and Baldwin, 2000). They aid in nitrogen management by increasing C:N ratios, needed for nitrogen mineralization (Creamer and Bennett, 1997). Also, polyculture cover cropping of non-legumes with legumes drive biological nitrogen fixation in legume species by non-legumes capturing nitrogen from soil reserves increasing the nitrogen demand for polyculture growth (Creamer and Bennett, 1997). Due to the benefits of cover cropping on soil nutrient properties, production may be particularly valuable in high tunnel systems.

Winter cover cropping in field studies reduces fallow periods during low-production seasons, creating the opportunity to improve degraded soils, reduce nutrient losses, and protect topsoil (Yongqiang Tian et al., 2011). Cover cropping during fallow growing seasons has been strongly recommended in the literature (Kim et al., 2013; Tribouillois et al., 2016; Belfry et al., 2017). Replacing fallow periods with cover crops helps increase soil reserves of inorganic soil N post-harvest (Tonitto et al., 2006). However, many high tunnel growers do not have a fallow period in their production system in winter. Similarly, the practical use of summer cover crops has been disputed, because of the cost of growing summer cash crops during the cover crop rotation (Bayer et al., 2006). Nevertheless, careful planning of cover crop rotations may yield benefits on soil health that outweigh its opportunity costs.

Despite the lack of fallow periods in high tunnel systems compared to open field systems, high tunnel soils are not exempt from the deleterious effects of intensive production practices on soil quality (Knewtson et al., 2012). Proper selection of winter and summer cover crop species/mixtures can yield varying results, making planning imperative (Barel et al., 2018). Buckwheat has been used in vegetable production systems as a short-window summer cover crop not only for its weed suppression ability, but because of its early emergence and rapid growth rate (Saunders Bulan et al., 2015). Consequently, summer cover crops can be incorporated in cropping rotations in short windows, between the harvest of summer cash crops and winter cash crops, allowing these cover crops to satisfy nutrient demands for subsequent winter crops (Weiler et al., 2018). Though winter covers typically require a longer growing season than summer cover crops, winter cover crop quantity and quality can be manipulated with mixtures (Barel et al., 2018). Also, their use can influence soil quality for subsequent spring cash crops.

Analyses of the profitability of cover cropping in vegetable production farming has had variable results. Profitability is dependent on many other factors including site location, management strategies, and subsequent cash crop (Belfry et al., 2017). Because of the delayed impact of cover cropping on growing systems, cover cropping should be considered a soil investment (Belfry et al., 2017).

Cover Cropping and Soil Physical and Chemical Properties

Cover crops can change the soil's physical structure through mechanical action of its combined root system, or by protecting the topsoil (Veiga et al., 2017). Incorporating cover crops such as red clover (*Trifolium pratense*) or radishes (*Raphanus sativus*) can alleviate soil compaction do to deep rooting (Buric, 2012; Parvatha, 2016; Rivers et al., 2018). Clover and radish roots can grow up to three feet in one cropping season (Buric, 2012). These deep roots increase soil nutrient reserves and provide a stable environment and microclimate that promotes complex arthropod communities (Parvatha, 2016; Rivers et al., 2018).

The above-ground detritus from terminated cover crops can be used as a substitute for plastic mulches used on farm in vegetable crop production (Campiglia et al., 2010). As a mulch, terminated cover crops protect the topsoil, preserve soil moisture, and increase soil water holding capacity (Campiglia et al., 2010). Plant residue decomposition affects various soil properties such as nutrient availability, pH, and soil water content (Frouz, 2018).

Cover crops are low-risk fertilizers, they have minimal and/or positive long-term impacts on the soil, water resources, and air quality (Veiga et al., 2017). Cover crops are used as green manures (Leslie et al., 2017). Green manuring is a management practice used as an alternative to mineral fertilizers, farmers typically use them to increase the soil organic matter (Kim et al., 2013). Green manures also "increase soil N availability for the next crop once their residues mineralize, allowing less N fertilizer to be applied" (Tribouillois et al., 2016). Cover crops add labile organic carbon to the soil, lending both economic and environmental benefits (Veiga et al., 2017). Research suggests that utilizing cover crops in minimum tillage systems can enhance the long-term pools of soil organic matter (Steenwerth and Belina, 2008). Studies have shown that while carbon additions from cover crop species may not be significantly different between most species, the carbon additions are significant compared to not using cover crops (Veiga et al., 2017; Steenwerth and Belina, 2008).

Cover crop decomposition is determined by soil moisture, climatic conditions, and C:N ratios (Belfry et al., 2017). The capacity of leguminous cover crops to fix nitrogen is widely noted, and research suggests that an integrated approach of using legume-fertilizer with conventional fertilizers for vegetable production may be more practical as solely legume-fertilized systems can result in up to 50% reduction in crop yields relative to conventional fertilization (Tonitto et al., 2006).

Cover Cropping and Soil Biological Properties

Cover cropping can increase soil nutrients and arthropod abundance and species diversity (Pearsons and Tooker, 2017). Cover crops provide a stable environment and microclimate that promotes complex arthropod communities and activity (Buchanan and Hooks, 2018; Rivers et al., 2018). Cover crop residues have higher percent humidity and provide food resources that support arthropods compared to fallow plots (Shearin et al., 2008). In addition, cover crop residues provide insulation from cold temperatures, which enhance survival of arthropods (Shearin et al., 2008). For example, greater Colorado potato beetle *(Leptinotarsa decemlineata)* mortality was observed when cover crop mulch residue was removed from the soil surface during the winter season (Milner et al., 1992). Although Colorado potato beetle is considered a pest on most agricultural crops, this finding suggests the influence of cover crop species on arthropod abundance.

Quintanilla-Tornel (2016) investigated the effects of sunn hemp (*Crotalaria juncea*) cover crop residues on belowground arthropods. Spider (Araneae), carabid beetle (Carabidae), and earwig (Dermaptera) populations higher in sunn hemp (*Crotalaria juncea*) treatments (Quintanilla-Tornel et al., 2016). Sunn hemp also promotes an increase of fungivorous nematodes, increasing the soil food web structure and complexity (Leslie et al., 2017; Quintanilla-Tornel et al., 2016; Wang, K.-H et al., 2011a; Wang, K-H et al., 2011b). Incorporating cowpea and buckwheat cover crops also attracted herbivorous species in vegetable production systems (Quintanilla-Tornel et al., 2016). Other cover crops that have been identified through research to influence belowground organisms include sunn hemp, cowpea, buckwheat, and barley (*Hordeum vulgare*) (Leslie et al., 2017; Quintanilla-Tornel et al., 2016).

In a study evaluating the influence of cover crop mixtures on above ground arthropod abundance on a cucurbit vegetable farm, plots of clover cover crops had twice as many arthropods as bare plots (Buchanan and Hooks, 2018). Arthropod communities can also be influenced by cover crop management practices such as: termination, planting date, tillage, etc (Rivers et al., 2018). For example, carabids were found to be more abundant in reduced tillage systems (Rivers et al., 2018).

The effects of cover crop mixtures on arthropod abundance may be cover crop species and season specific (Rivers et al., 2018). Nonetheless, indices of soil species diversity have been used to make inferences about soil ecosystem stability and resilience (Ferris and Tuomisto, 2015). Belowground arthropods (insects and mites) respond to disturbances and changes in environmental conditions, which may allow them to serve as probes for ecosystem change (Mattoni et al., 2000; Kremen et al., 1993). Belowground arthropods may be affected by alteration in agricultural management practices (Benckiser, 1997). The effects of cover cropping on ecosystem services is well-studied, however, the influence of cover crop mixtures on arthropod abundance needs to be investigated (Buchanan and Hooks, 2018).

Research Objectives

Agroecosystems are altered habitats (Pearsons and Tooker, 2017). These altered habitats are targets for soil degradation. In high tunnel vegetable production systems, the effects of intensive production practices can be more pronounced. Also, growers are unlikely to adopt cover crops due to the lack of fallow periods in most high tunnel systems. This project will investigate how cover crop rotations affect soil chemical and biological properties in high tunnels. Previous research has shown that within the first year of cover cropping in the open-field soil health may be improved and nutrient leaching can be reduced (Belfry et al., 2017). Therefore, research that identifies cover crops that can be integrated in intensive crop rotations in high tunnels will help expand the soil heath management options for high tunnel growers. The project objectives are the following:

- ❖ Develop practical cover cropping recommendations in high tunnels that lead to increased soil health
- ❖ Test the performance of certain cover crop species alone and in mixtures within intensive high tunnel crop rotation
- ❖ Assess belowground arthropod abundance in high tunnels and how abundance is affected by cover crops and other farming practices
- ❖ Monitor trends in belowground arthropod diversity and abundance after cover crop termination and as the organic matter decomposition.

Chapter 2- Performance of summer and winter cover crops in high tunnels in the Central United States

Abstract

The use of high tunnel systems for vegetable crop production is increasing throughout the United States. High tunnels offer growers environmental protection, season extension, increased crop quality and yield, and pest and disease exclusion. In contrast to greenhouse production, high tunnel production is typically soil-based. Intensive cultivation and/or reduced crop rotation intervals are typical in high tunnels and can lead to degradation of soil health. The objectives of this study are to identify summer and winter cover crop species that are viable for high tunnel systems and determine their impact on soil nutrient pools and arthropod abundance. High tunnel experiments were conducted in 2018 and 2019. There were eight cover crop treatments planted in each season, which included grass and legume combinations as well as a weed-free bare control; hairy vetch *(Vicia villosa)*, and cowpea (*Vigna unguiculata)* were the legumes used. In the winter experiments, the rye (*Secale cereal*) and hairy vetch treatment resulted in the highest biomass and cover crop nitrogen contributions *($P < 0.05$)*. During the summer cover crop trials, the summer cover crop N contribution (lbs/acre) was highest for the sorghum-sudangrass (*Sorghum x drummondi)* treatment averaging 99.8 lbs/acre *($P < 0.05$)* across both years. Trends in soil total carbon (STC), organic matter (OM), and soil total nitrogen (STN) revealed statistically significant effects of cover cropping on soil properties in both seasons. The findings of this study suggest that using cover crops in high tunnels is an effective way to increase soil health and we have identified several summer and winter cover crop species that are successful in high tunnel systems.

Introduction

High tunnels are semi-permanent, moveable, or temporary structures constructed with a metal, wooden or polyvinylchloride (PVC) frame and a polyethylene film covering (Carey et al., 2009; Knewtson et al., 2012). Research in the 1990's surrounding the potential of these structures for vegetable crop production bolstered their increased use for warm-season crops such as tomato (*Solanum lycopersicum*) (Carey et al., 2009). One of the most important benefits of high tunnel production is the microclimate they create allowing growers to produce crops year-round in some climates (Lamont, 2009). In temperate regions, high tunnels warm the air and soil offering farmers an extended growing season (Lamont, 2009). Increased temperatures in spring and extended warming into the fall make high tunnel microclimates favorable for farmers (Lamont, 2009). Protected cultivation enables growers to control wind velocity, ambient air temperature, light intensity, and moisture in growing system (Wittwer and Castilla, 1995). High tunnels can allow more uniform light distribution on foliage increasing photosynthesis during production (Kadir et al., 2006). The modified climate in high tunnels improve production in areas with field seasons of moderate temperatures and limited duration, thereby, extending the growing season (Rader and Karlsson, 2006). High tunnels can also produce high-value crops earlier in the season than field-grown crops (Conner et al., 2009). Unlike hydroponic- and soilless media-based greenhouse systems, high tunnel crops are grown directly in the soil beneath these structures.

Despite the benefits of high tunnel crop production to farmers and consumers, growing practices used in high tunnel systems are not always ideal for soil health. Growers typically utilize intensive cultivation practices in high tunnels, which can lead to high environmental costs like soil degradation (Norris and Congreves, 2018). Some intensive production practices with negative effects on soil health include short crop rotations, over-use of fertilizers, and frequent tillage (Pereira et al., 2018). High tunnel growers typically till after each cropping cycle, remove crop residues, and plant a subsequent cash crop (Waterer, 2003). This cycle can be repeated multiple times per year, where the microclimate in high tunnels allows for year-round production (Lamont, 2009).

Management practices in protected cropping systems can significantly affect soil chemical properties (Ge et al., 2011; Meyer, 2016). High fertilizer use coupled with low living plant cover can lead to soil and groundwater degradation (Tonitto et al., 2006). Improper nutrient management can also lead to an accumulation of phosphorus with marked imbalances of N, P, K for optimal vegetable crop production (Ju et al., 2007). There are multiple reasons for the increased use of fertilizers in high tunnel systems such as: (1) vegetable crop nutrient demands (2) high economic value of extra yields (3) farmer's gap in knowledge of fertilizer and irrigation water best practices (Congreves and Norris, 2018; Ju et al., 2007). Changes in soil chemical properties can accompany changes in belowground arthropod activity, soil aggregate stability, and nutrient cycling (Haynes and Tregurtha, 1997). The most significant change is in soil organic carbon and organic matter (Haynes and Tregurtha, 1997).

The use of cover crops has been suggested as a method to improve soil properties, both structural and chemical (Belfry et al., 2017; Kim et al., 2013; Tribouillois et al., 2016). Cover crops in vegetable crop production can be grown alone or in mixtures (Barel et al., 2018). Studies found grass species typically outperformed non-grass species in aboveground and belowground biomass yields (Barel et al., 2018). Winter legumes such as vetch, may have low root biomass compared to non-legume species, but can have twice as much nitrogen concentration as grassy species due to their ability to fix nitrogen (Barel et al., 2018). Nitrogen fixation has a strong effect on increasing potential soil nitrogen reserves (Barel et al., 2018).

Nitrogen deposition from legume cover crops increases as the crop's biomass increases (Creamer and Baldwin, 2000). Research on cowpea development shows that nitrogen in cowpea tissues can double between weeks 5 and 7 (Franzluebbers et al., 1994). Non-legume crops such as ryegrass, sorghum-sudangrass, and buckwheat (*Fagopyrum escultentum*) are recommended for their ability to aid in weed suppression, increase soil organic matter, and manage soil nitrogen (Creamer and Baldwin, 2000). They aid in nitrogen management by increasing the carbon-to-nitrogen (C:N) ratio, thereby improving nitrogen release in soil (Creamer and Bennett, 1997). Polyculture cover cropping of non-legumes with legumes drive biological nitrogen fixation in legume species. This occurs by non-legumes capturing nitrogen from soil reserves, increasing the nitrogen demand for polyculture growth (Creamer and Bennett, 1997). Due to the benefits of cover cropping on soil nutrient properties, this technique may be particularly valuable in high tunnel systems.

Winter cover cropping in open field studies reduces fallow periods during low-production seasons, creating the opportunity to improve degraded soils, reduce nutrient losses, and protect topsoil (Yongqiang Tian et al., 2011). Replacing fallow periods in the open field with cover crops has also been shown to help increase inorganic soil N post-harvest (Tonitto et al., 2006). However, many high tunnel growers do not have a fallow period in their production system in winter. Similarly, the utility of summer cover crops is not clear due to the implicit opportunity cost of growing summer cash crops during the cover crop rotation (Bayer et al., 2006). Nevertheless, careful planning of cover crop rotations may yield benefits on soil health that outweigh the opportunity cost of not growing a cash crop.

Despite the lack of distinct fallow periods in high tunnel systems compared to open field systems, high tunnel soils are not exempt from the deleterious effects of intensive production practices on soil quality (Knewtson et al., 2012). For growers that specialize in season extension with cool-season crops, a summer cover cropping cycle may fit their production system better than winter cover crops. Proper selection of winter and summer cover crop species/mixtures can yield varying results, making planning imperative (Barel et al., 2018). Cover crops such as buckwheat have been used in vegetable production systems as a summer cover crop not only for its weed suppression ability, but because of its early emergence and rapid growth rate (Saunders Bulan et al., 2015). In Kansas, summer cover crops could be incorporated into crop rotations in shorter production windows such as: between the harvest of spring or early summer cash crops and fall (cool-season) planting, which allows these species to address nutrient demands for subsequent fall or winter crops (Weiler et al., 2018). Though winter covers typically require a longer growing season than summer cover crops, winter cover crop quantity and quality can be manipulated with mixtures (Barel et al., 2018). Also, their use can influence soil quality for subsequent spring cash crops.

High tunnel growers may not use cover crops due to the lack of a distinct fallow period in most high tunnel systems. More specifically, many high tunnel growers prefer a summer fallow period whereas others would utilize winter fallow periods, based on their local climate, potential markets, and farm operational needs. Therefore, our research objectives are to (i) identify legume and non-legume cover crop species that perform well, alone and in mixtures, in regard to biomass accumulation and nitrogen contribution in high tunnels in summer and winter cropping cycles; and (ii), examine the impact of summer and winter cover crop species on soil carbon, nitrogen, and organic matter.

Materials and Methods

Two independent experiments were conducted; one examined winter-hardy cover crops and one utilized cover crops in summer. Each experiment used cash crops incorporated into the production cycle (described below). The experiment site was located at the Kansas State University Olathe Horticulture Center in Olathe, Kansas (38.884347 N, 94.993426 W). The soil type is Chase silt loam soil (pH = 6.3). The research station is within USDA Plant Hardiness zone 6A. Experiments were conducted from 2017-2019 in a high tunnel 200 ft long and 15 ft wide that has been used continuously for vegetable research for over 10 years. The high tunnel was managed according to National Organic Program (NOP) standards. Cantaloupe (*Cucumis melo*) was grown during the 2017 cropping season. In the summer and winter cover crop trials, cash crops were planted 14 days after cover crop termination to simulate a grower production schedule. HOBOware weather data loggers (Onset Computer Corporation, Bourne, MA) were installed in the high tunnel in one of the control plots (bare soil) for each growing season to monitor temperature and relative humidity, soil moisture, and soil temperature. Weather data during cover crop growth is presented in Table 2-1.

Experimental Design

Each experiment utilized a 51 ft x 24 ft area of the high tunnel with the summer cover crops on the north end, and the winter cover crops in the center of the tunnel. The experiments were arranged in a split-plot randomized complete block design with the presence or absence of legumes as the main plot factor and the subplot factor was the variety of non-leguminous crops that were tested. Each experiment consisted of four replications, which were divided by 18 in and 2 ft aisles that were oriented perpendicular and parallel with the length of the tunnel, respectively. The individual sub-plots were 4 ft x 5 ft. The cover crop species tested were selected based on hardiness and regional cover crop data (Buric, 2012). No fertilizers were used in the two experiments to more accurately monitor changes in soil nutrient properties based on the cover crop treatments. The changes in soil nutrients were monitored through soil sampling performed at that start of the experiments and multiple time points after cover crop termination. Weather data during the cover crop study is recorded in Table 2-1 and the cover crop treatments and their seeding rates are listed in Table 2-2.

Cover Crop Rotations

The experimental plots were tilled using a two-wheel tractor with a rear-tine tiller (BCS Model 732, BCS America, Texas). After tilling, cover crops were broadcast seeded by hand, and the plots were irrigated using overhead sprinklers to field capacity. Once the cover crops germinated, they were irrigated as needed to prevent wilting. Aboveground cover crop heights were measured at termination. Three cover crop height measurements were taken for each plot and the height was averaged.

In both experiments, cash crops were planted 14 days after cover crop termination. For the summer experiment, cover crops followed a spring kale (*Brassica oleracea)* transplant crop rotation and were succeeded by fall-seeded spinach (*Spinacia oleracea)*. For the winter cover crop experiment, 'Declaration' bell peppers (*Capsicum annuum*) were transplanted following termination and subsequent tillage.

Biomass Sampling and Termination

At cover crop termination, biomass samples were collected using a 0.1 m square quadrat (Parr et al., 2011). The quadrat was held in place on the ground and shears were used to cut the aboveground plant matter within the quadrat (Parr et al., 2011). Samples from each plot were collected and dried for at least 72 hours using a Grieve SC-400 forced air dryer at 65°C (Parr et al., 2011). In addition to the biomass samples collected from each plot, one 5 g biomass sample was collected from each subplot for tissue analysis. Cover crop subsamples were sent to Waters Laboratory (Owensboro, Kentucky) to obtain percent nitrogen content of biomass. Percent nitrogen was determined using an acid-digestion method, after which the samples were processed through combustion on a LECO elemental analyzer machine (LECO, St. Joseph, MI).

After sampling for plant biomass was completed, the plots were terminated using hand shears to shred biomass into smaller pieces for subsequent incorporation. Furthermore, all biomass was retained within a respective plot on the soil surface until incorporation 7 days later using a two-wheel tractor tiller. All plots were irrigated afterward to promote cover crop residue decomposition (Lee et al., 2014). Seven days after termination, a tiller was used to prepare the soil for planting the cash crop.

Winter Cover Crop Experiment

In the winter cover crop experiment, hairy vetch and no-legume were the main plot factors and three non-leguminous cover crop species were the sub-plot factors. There were eight cover crop treatments including: rye, hard red winter wheat (*Triticum aestivum*; W), triticale (×*Triticosecale*; T), and a weed-free control plot (BC), hairy vetch (*Vicia villosa*; V), rye and hairy vetch (R+V), hard red winter wheat and hairy vetch (W+V), and triticale and hairy vetch (T+V). The cover crops were seeded on 19 October in 2017 and 15 October in 2018 and terminated on 9 May in both years. Thus, winter cover crops were grown for 203 and 207 days in 2018 and 2019, respectively. Baseline soil samples (n=32) were collected from each cover crop treatment plot prior to seeding cover crops on 19 October in 2017 and 15 October in 2018.

Summer Cover Crop Experiment

The cover crop species included in the summer experiment are as follows: buckwheat (B), Japanese millet (*Echinochloa esculenta*; M), sorghum-sudangrass (SS), and a weed-free bare control plot (BC), cowpea (C), buckwheat and cowpea (B+C), Japanese millet and cowpea (M+C), and sorghum-sudangrass and cowpea (SS+C). In 2018, the summer cover crops were grown for 77 days from 9 June to termination on 4 September, 2018. Due to the large amount of biomass produced in 2018, the growth period for the 2019 trial was shortened. The cover crop residue in 2018 was too high in some of the plots, such that subsequent seeding of spinach did not germinate. Therefore, cover crops were grown for 56 days from 11 June to 6 August in 2019. Baseline soil samples (n=32) were collected from all plots on 9 June 2018 and 11 June 2019 before the seeding cover crops.

Soil Sampling Protocol Winter and Summer

Soil samples (n=32) were collected from each plot to determine total carbon (C), total nitrogen (N), and organic matter (OM) before each cover crop experiment and after termination (Arnet, 2010). Soil samples were collected using a soil probe from the central area of each plot at a six-inch depth (Gál et al., 2007). Each sampling area was inspected to ensure that no outside influences, such wildlife feces, were observed. Soil samples consisting of 128 g of soil from each plot were placed into a bucket for soil nutrient assessment. Soil cores collected were gently broken up in a bucket and large aboveground plant material was removed. Soil was then placed in plastic bags and stored in coolers prior to being submitted for analysis. Samples were transported to Kansas State University Soil Testing Laboratory (Manhattan, KS) for analysis of soil organic matter, total carbon, and total nitrogen. Soil organic matter was analyzed using the loss on ignition method (LOI), and soil total carbon and nitrogen was analyzed using A LECO

TruSpec CN Carbon/Nitrogen combustion analyzer (LECO, St. Joseph, MI) (Combs and Nathan, 1998). Total inorganic and organic carbon and nitrogen levels were reported on a percent weight basis, according to the TruSpec CN instrument method (LECO Corporation, 2005). For the winter experiments, baseline soil samples (n=32) were collected at cover crop seeding, and subsequent soil samples (n=32) were collected at termination (Day 0), four weeks post termination (Day 28), and eight weeks post termination (Day 56). In the summer experiments, baseline soil samples (n=32) were collected at cover crop seeding, and subsequent samples (n=32) were collected at cover crop termination (Day 0), two weeks post cover crop termination (Day 14) and eight weeks post cover crop termination (Day 56).

Statistical Analysis

Cover crop available nitrogen was calculated using a modified calculation from Sullivan and Andrews (2012). The calculation was plant available nitrogen (PAN; lb/a) = cover crop dry biomass (lbs/acre) x plant tissue N content (%) x estimated cover crop N use efficiency (50%). Data from the summer and winter experiments were normally distributed and met the assumption of equal variance??? and, therefore, were not transformed prior to analysis. For the summer and winter cover crops the effects associated with soil total carbon, total nitrogen, and organic matter during the two-year study were analyzed using one-way analysis, Tukey multiple comparisons, and ANOVA multiple effects tests in JMP statistical program (SAS Institute, Cary, North Carolina). Significance was based on α=0.05.

Results

Cover Crop Biomass and Nitrogen Contributions

Winter cover crops varied in biomass production over the two years with significantly higher biomass production in 2018 than 2019 ($P < 0.01$; Table 2-3; Table 2-4). Hairy vetch had low biomass production in the high tunnel in both years when planted alone (P < 0.0001; Table 2-3). In 2018, the top biomass producers were the R+V (8,756 lbs/acre) and T+V (8,617 lbs/acre) treatments ($P < 0.0001$). In the second year, biomass yields were much lower for all the treatments with many of the cover crops yielding similar results to the BC treatment. The highest biomass in the second year were the R, R+V, and W treatments ($P < 0.0001$). The average height of the winter cover crops in the tunnel in 2018 was 37.6 inches (Table 2-3). In 2019, the average plant height across all treatments was 22.9 inches (Table 2-4).

The available N provided by the individual cover crop species and mixtures are shown in Table 2-4. Among the treatments, R, R+V, and T+V provided the highest available N ($P < 0.001$; Table 2-5). Similar to the cover crop biomass, there were significant differences in the available N (lbs/acre) for each sampling year ($P<0.0001$; Table 2-5). In the first year of the winter cover crops, there were significant differences in cover crop N by treatment ($P < 0.001$). The treatments with the most available N in the experiment were the R, T+V, and R+V treatments ($P < 0.0001$; Table 2-5). In year two, available N was significant by treatment ($P < 0.0001$; Table 2-5) with the R, R+V, and W treatments performing the best in that year ($P < 0.0001$; Table 2-5).

In the summer cover crop experiment, the cowpea treatments performed well in both years ($P < 0.0001$) and summer cover crop biomass production in the high tunnel varied by treatment ($P < 0.0001$; Table 2-7). Similar to the winter cover crop experiments, there was higher biomass produced in year one (average of 8,495 lbs/acre) compared to year two (average of 6,267 lbs/acre) ($P < 0.05$; Table 2-7). In addition, the treatment effects on cover crop biomass were significant (*P < 0.0001*). SS and the SS+C treatments produced the most biomass in the first year of the experiment (*P < 0.0001*; Table 2-7). Cover crop type was also significant in the second year *(P < 0.001)* and the SS treatment outperformed all other treatments. In plots not containing sorghum-sudangrass, the SS treatment outperformed other treatments by magnitude of at least four times in 2018 and a magnitude of two times in 2019 (*P < 0.001*; Table 2-7). However, the M treatment and the C treatment biomasses were similar to the SS treatment (*P < 0.001*; Table 2-7). Available nitrogen from the summer cover crops were not significantly different between the two years (*P=0.3821*; Table 2-8). The SS, C, SS+C, and B treatments had the highest biomass yields (*P < 0.0001*). Despite a significant difference in cover crop biomass between year one and two, there were no significant differences in available N (*P= 0.0697*). In year one, SS, C, SS+C, and B treatments were significantly different from the other treatments (*P= 0.001*) and produced the highest amount of available N.

At termination summer cover crop heights in year one averaged 48.0 inches, however, SS and SS+C treatments were over 60.0 inches tall in year one (*P < 0.0001*). In year two, the height of the summer cover crops at termination averaged 36.0 inches, with SS and SS+C averaging 60 inches (*P < 0.0001*; Table 2-7).

Winter Cover Crops Increase Soil Nitrogen, Carbon, and Organic Matter

The amount of soil total nitrogen found at cover crop termination and eight weeks after varied by treatment (*P < 0.0001;* Table 2-9). Cover crop species contributed higher total nitrogen than the other species (*P < 0.0001;* Table 2-9). In year one of the winter study, the highest level of soil total nitrogen was found at cover crop termination (*P < 0.0001*; Figure 2-1). The W+V treatment at cover crop termination (Day 0) had the highest amount of soil total nitrogen (0.24%) ($P < 0.0001$; Table 2-8). Two weeks post-termination and the weeks following, soil total nitrogen significantly decreased ($P < 0.0001$; Figure 2-1).

In the soil total nitrogen analysis, year two had significantly lower soil total nitrogen at termination ($P < 0.0001$; Figure 2-1). The W, R, T+V, R+V, and T treatments had the highest soil total nitrogen ($P < 0.0001$; Figure 2-1). Unlike year one, in year two, soil total nitrogen was highest four weeks after termination ($P < 0.0001$; Table 2-9). The W and R treatments had comparably higher amount of soil total nitrogen at four weeks post termination (Day 28) in 2019 ($P < 0.0001$; Figure 2-1). Soil total nitrogen increased by 0.02% in R treatments and 0.03% in W treatments. There were significant differences in soil total carbon by treatment and by sampling day over the two years ($P < 0.001$; Table 2-9). The R+V treatment on Day 28 yielded the highest amount of soil total carbon in the study ($P < 0.0001$; Table 2-9). The R and V treatments on Day 14 had the highest soil total carbon in year one. The soil total carbon in year two indicated that the R+V treatment to be the treatment with the highest amount soil total carbon ($P < 0.0001$). The highest amount of total carbon was found at Day 28 with a mean of 2.54% for all treatments.

There were differences in soil organic matter in the winter experiment by year ($P < 0.0001$; Table 2-9). In addition, there were significant differences in soil organic matter by treatment ($P < 0.0001$) and by day ($P< 0.01$). The R+V treatment and the W+V treatment had the highest amount of soil organic matter in the experiment ($P < 0.0001$; Table 2-9).

In year one, soil organic matter varied by day after termination ($P < 0.0001$). R+V, R, V, and T+V treatments had the highest amount of soil organic matter over the course of the study (P < 0.0001). In year two, the highest amount of soil organic matter was recorded on Day 28 ($P < 0.0001$) with an average of 4.2%. Organic matter by treatment showed the R+V and W+V treatments had the highest level of soil organic matter ($P < 0.0001$; Table 2-9).

Summer Cover Crops Increase Soil Nitrogen, Carbon, and Organic Matter

In the summer experiment, there was a significant effect of year ($P < 0.0001$), day ($P < 0.0001$), cover crop treatment ($P < 0.0001$), day x treatment ($P < 0.0001$), and year x day x treatment ($P < 0.0001$) on soil total nitrogen. The second year had a significantly higher soil total nitrogen than year one ($P < 0.0001$; Table 2-5). The highest soil total nitrogen over the two years was observed on Day 56 in year two ($P < 0.0001$; Table 2-10).

In year one, the B+C, B, and SS treatments had the highest amount of soil total nitrogen ($P < 0.0001$; Table 2-10). Soil total nitrogen was highest on Day 56 in all treatments ($P < 0.0001$; Table 2-9). In year two, the B+C and the M+C treatments had the highest percentage of soil total nitrogen ($P < 0.0001$). The B+C treatment on Day 56, M treatment on Day 14, and B on Day 14 had the highest soil total nitrogen than all other treatments ($P < 0.0001$; Table 2-10). Soil total carbon was varied by year ($P < 0.0001$). Year two had the highest soil total carbon and the B+C and SS treatments in year two were significantly higher than all other treatments ($P < 0.0001$; Table 2-10). The B+C, SS, B, and M+C treatments had the highest soil total carbon across the two years ($P < 0.0001$). In year one, the highest soil total carbon was at day 56 which was between 2.5% and 2.6% ($P < 0.0001$). The treatments with the highest soil total carbon were the SS, B, and B+C treatments ($P < 0.0001$). In year two, soil total carbon was similar for days 14, 28, and 56 ($P < 0.0001$). The treatments with the highest soil total carbon were the B+C treatment and the SS treatment ($P < 0.0001$).

There was no difference in soil organic matter by year (n=2) in the summer cover crop experiment ($P = 0.0763$), however soil organic matter varied by day($P < 0.0001$), treatment ($P < 0.0001$), and day x treatment ($P < 0.0001$). Soil organic matter for multiple treatments were highest on Day 14 and 56 ($P < 0.0001$). In year one, the BC and M treatments had the lowest soil organic matter (*P < 0.001*; Table 2-9). In year two, soil organic matter was highest at Day 14 (*P < 0.0001*). The SS, B+C, and B treatments had the highest soil organic matter (*P < 0.0001*; Table 2-10).

Discussion

The performance of the cover crops in the high tunnel were similar to results reported in other studies of cover cropping in the open field. In other studies, rye produced between (7,000 to 8,000 lbs/acre) of biomass and sorghum-sudangrass produced up to 18,000 lbs/acre when planted in the open field (Brennan et al., 2011; Buric, 2012). Cowpeas produced between 3,000 and 4,000 lbs/acre, and buckwheat 1,600 to 2,400 lbs per acre in field studies (Buric, 2012). However, hairy vetch yields in the high tunnel were not comparable to the open field (Buric, 2012). Hairy vetch in the open field can produce between 3-5 t ha^{-1} which is between 2,400 and 4,000 lbs/acre (Lu et al., 2000). In our study, the highest yield was 92 lbs/acre in 2018. There was some evidence of grazing from wildlife, which may have contributed to poor growth. The use of polyculture cover cropping is growing in vegetable production systems (Brennan, et al., 2011; Creamer and Bennett, 1997). Winter polyculture mixes can help species that may struggle to overwinter when planted alone (Buric, 2012; Creamer and Bennett, 1997). All of the species of cover crops that were tested in the winter experiment, with the exception of hairy vetch, overwintered successfully and performed comparably with results from open field data where the same species were used (Buric, 2012; Freeman, 2014). Creamer and Bennett (1997), found rye to be competitive with other species. In most mixtures including rye at least 80% of the measured above ground biomass in those mixtures was composed of rye just before termination (Creamer and Bennett, 1997). In our study, the above ground biomass of rye in the R+V mixtures comprised about 85% of the mixture at termination. However, competition from other species could not have impacted hairy vetch growth, since there were low yields when it was grown alone as well as in mixtures in both sampling years. Previous studies have shown that fall planted hairy vetch grows slowly, often providing minimal winter soil cover (Lawson et al., 2015). Time of planting and termination are important for overwintering cover crops, as establishment and biomass accumulation are affected by the amount of growing degree days for the crop (Lawson et al., 2015). This research suggests that hairy vetch is not an ideal winter cover crop for high tunnels in the Central U.S., however, alternate planting and termination times for hairy vetch in future studies may result in higher biomass production. For instance, delaying termination of hairy vetch by 14 days resulted in biomass increases between 35 and 61% (Clark et al., 1995; Lawson et al., 2015, Wagger, 1989). However, in a high tunnel setting, delaying termination of hairy vetch may be unfavorable, altering spring cash crop production schedules.

The SS treatment had the highest biomass (lbs/acre) in the summer cover crop experiment. Sorghum-sudangrass has an aggressive root system and is taller and more drought tolerant than forage sorghum (Buric, 2012). SS cover crops can yield up to 18,000 lbs/acre (Buric, 2012) in the open field and similar performance was found in our high tunnel study. This suggests that SS may be a favorable cover crop for high tunnel production systems. The timing of cover crop termination is an important management strategy (Buric, 2012). The timing of termination was earlier in the second year of the summer experiment, due to an unmanageable amount of biomass that grew in 2018. As a result, the biomass was lower in 2019 by approximately 2,000 lbs/acre. In 2018, the sorghum-sudangrass plants were difficult to terminate due to lignified stalks and a massive amount of biomass. Terminating the summer cover crops a month earlier in 2019 enhanced the process of planting the subsequent cash crop due to less residue on the soil surface after tillage. In 2018, the SS plants were pressing on the ceiling of the high tunnel at termination. Since available soil nitrogen was similar between 2018 and 2019, our data suggests that high tunnel growers interested in utilizing cover crops as a primary source of N may be able to terminate SS cover crops earlier. This situation has been seen in open fields with cover crops, the nitrogen concentration of the cover crop declines as plants mature (Alonso-Ayuso, 2014; Lawson et al., 2015; Wagger, 1989). The mature, lignified stalks may have led to lower soil total nitrogen between 2018 and 2019. The higher C:N ratio amongst the mature biomass in 2018 may have had a lower rate of decomposition than the more tender crops in 2019.

In field studies, cowpeas can produce up to 4,000 lbs/acre of dry biomass (Sarrantonio, 1994). In our study were produced between 5,000 to 6,000 lbs/acre in our high tunnel system. The contribution of cowpea to soil nitrogen was significant. Cowpeas were competitive within the cover crop mixtures, comprising on average approximately 45% of the overall biomass when grown with other species. In the literature, nodulation of cowpeas is vigorous, making it suitable as a green manure (Duke, 1981; Franzluebbers et al., 1994). In our study, nitrogen contributions from C treatment was competitive with the amount of nitrogen captured by the SS treatments despite lower dry biomass production. The abundant growth and high nitrogen contributions from the C treatment in the study in late and early termination confirm its practical use in Midwest high tunnels during short rotations.

We observed significant changes in soil total nitrogen and total carbon in both years for summer and winter cover crops. Typically, observable differences in soil nutrient availability are difficult to measure in short-term studies like the ones that we conducted (Tian et al., 2011). In several studies using cover crops in the open field, significant changes in soil nutrient properties occurred after 3 or more years of cover cropping (Balkcom and Reeves, 2005; Blevins et al., 1990; Fontes, 2017; Oyer and Touchton, 1990). Research suggests that these types of longerterm studies are required for significant effects of cover cropping on soil nutrient pools to be realized (Tian et al., 2011). However, the body of the research on cover cropping is from open field trials rather than high tunnels, which may contribute to this phenomenon (Creamer and Bennett, 1997; Creamer and Baldwin, 2000; Freeman, 2014; Saunders Bulan et al., 2015). In both the winter and summer studies, significant increases in soil total carbon, soil organic matter, and soil total nitrogen were observed within the first two years of cover cropping. This data suggests that the use of cover crops in high tunnel systems may provide a faster impact on soils than in the open field. This may be due to the protection offered in high tunnel systems that regulates soil moisture, soil temperature, and ambient temperature conditions. All these properties along with soil nutrient supply affect respiration and mineralization, thereby affecting the amount of nutrients available in the soil (Bond-Lamberty and Thomson, 2010; Hursh et al., 2017; Stottlemyer, 2001).

One of the reasons that long-term research is suggested for winter cover crops is because their performance typically varies considerably among years (Brennan, and Smith, 2005). In 2018, biomass production among the winter cover crops was higher in 2019 by about 4,000 lbs/acre. Interestingly, soil total nitrogen and organic matter ranges were higher in the second year of cover cropping. This suggests a possible cumulative effect of winter cover cropping, as increases in soil nitrogen and carbon occurred in our trials despite biomass yields being lower in the second year (Steenwerth and Belina, 2008; Veiga et al., 2017). Another possibility is that when biomass was high in 2018 it used more soil nitrogen.

C:N ratios and other soil physical and biological properties influence mineralization rates making recommendations for growers who use cover crops in agro-ecosystems difficult (Melkonian et al., 2017). In general, legume/non-legume combinations are favorable cover crop mixtures because they provide more nitrogen for mineralization (Buric, 2012; Creamer and Baldwin, 2000). Increased mineralization rates affect soil nutrient release (Buric, 2012). Soil organic matter fluctuated throughout cover crop breakdown in both experiments. In the winter experiments, the R+V, T+V, and T treatments had the greatest declines in soil organic matter between day 28 (four weeks after termination) and day 56 (eight weeks after termination). Similarly, soil carbon and nitrogen were highest at day 28. This finding suggests that winter cover crop nitrogen release is highest four weeks after termination in high tunnel systems. Growers using cover crops in open fields for corn production typically plant corn crops 4-6 weeks after termination estimating this time frame as the period where cover crop nutrients are released (Brennan et al., 2011). In high tunnel systems, nutrients from winter cover crops may be released earlier than in the open field, due to the modified climate in high tunnels that can increase heat and humidity, increasing mineralization and respiration rates. In contrast to the winter cover crops, soil total nitrogen was the highest 14 days (two weeks) after termination during the summer cover crop experiments. These data suggest that farmers interested in utilizing summer cover crops in high tunnels may have the best opportunity of using soil nutrients for a cash crop 14 days after termination. However, this timeline may vary for high tunnel growers based on cover crops grown and various soil conditions (soil type, soil moisture, and soil abiotic and biotic properties) (Melkonian et al., 2017).

Soil respiration governs CO_2, CH_4, mineralized nitrogen, and dissolved organic carbon release (Stottlemyer, 2001). Respiration occurs through autotrophic and heterotrophic processes (Hursh et al., 2017; Bond-Lamberty and Thomson, 2010). In studies investigating microbial activity in soils, soil respiration and nitrogen mineralization were affected by soil temperature, moisture, and soil nutrient supply (Sottlemyer, 2001). Soil temperature is a dominant driver in soil respiration rates and nitrogen mineralization (Hursh et al., 2017; Sottlemyer, 2001). The average soil temperatures at 14 days post cover crop termination for the summer experiment was 85°F, while at 14 days post cover crop termination for the winter cover experiment it was 72°F. Since soil moisture content was similar in both experiments during termination, higher soil temperatures and nutrient supply by summer cover crops may have enhanced respiration and contributed to earlier releases of soil nitrogen and carbon than in the winter experiment.

Nitrogen is often the most limiting nutrient for vegetable crop production, and can be lost by leaching (Freeman, 2014). In the summer cover crop experiments, soil total nitrogen increased during cover crop decomposition with the cumulative effect of two years of cover cropping leading to increased soil nitrogen in all cover crop treatments. In contrast, soil nitrogen in the 2018 winter experiment declined after cover crop termination which conflicts with previous research ((et al., 2018). This inverse effect of cover cropping on soil total nitrogen may have occurred due to nitrogen immobilization during cover crop decomposition (Barel et al., 2018). High carbon to nitrogen ratios of cover crops such as wheat, rye, and triticale may have immobilized soil nitrogen for the decomposition process.

Mean values of N, OM, and C increased from baseline to the second year's final sampling point ($P < 0.0001$). The largest increase was in the summer experiment, where soil total carbon increased from 2.4% at baseline to 2.6% in year two. In the winter experiment, there were significant changes in soil N and C ($P < 0.0001$). However, in contrast to the summer experiment, winter soil organic matter had an overall decrease when compared to year one baseline data. It is not clear why this trend occurred or if it would happen again in future studies.

Although this report provides valuable information for high tunnel growers in the Central U.S. on the effect of cover cropping on high tunnel soil total nitrogen, total carbon and organic matter, there were some limitations in the study. The plot sizes utilized were small and subject to edge effects and inter-plot interference. Therefore, aisles were between plots and plot residues were retained within their space during termination and incorporation. Soil sampling was conducted in the central area of each plot. High tunnel production space is often limited on commercial farms and research stations and experiments with cash crops like tomato and spinach are often smaller than in similar open field trials (Eaton et al., 2016; Marshall et al., 2016). Furthermore, this study was not repeated in other locations. Future research that includes on-farm cover crop evaluations in high tunnels would provide additional information for researchers regarding the use of equipment and other methods for terminating and incorporating cover crops. Weed pressure was not measured in this study but is an important benefit of cover cropping. Cover crops compete for space with weed crops, reducing the amount of weed growth in growing systems (Saunders Bulan et al., 2015; Brennan and Smith, 2005; Campiglia et al., 2010). In the case of the winter cover crops, after cover crops were terminated, fabric mulch was utilized for weed control, which is typical for solanaceous crops. Growers interested in utilizing cover crops in high tunnels may choose to do so for weed management, making this area of research important for future studies. Additionally, research that extends beyond two years may be necessary to identify the long-term effects of cover cropping in high tunnel systems. Our study was conducted for two years and revealed short-term cumulative effects of cover cropping in high tunnels. Despite changes in nutrient pools being statistically significant, these changes were modest, and the long-term use of cover crops may have more dramatic effects on soil health and nutrient availability. Lawson (2015) reported that six years of cover cropping resulted in soil available nitrogen up to 86 lbs/acre in rye and hairy vetch mixtures, 55 lbs/acre in rye treatments, and 106 lbs/acre for hairy vetch treatments.

Research documenting the influence of summer and winter cover crops on cash crop quality and yield would provide useful grower recommendations. In our study, bell peppers and spinach were planted two weeks after the cover crops were terminated. There was no fertilizer used in the study and yields were relatively low for both crops. Future research studies should include detailed yield trials (with and without fertilizer) on the subsequent cash crop as well as the effects of cover crop residues on cash crop germination and/or initial growth after transplanting. Although we did not collect data related to these issues, we observed that cover crops that provided very high biomass could become problematic in regard to residue management. Residue management is an important issue in open field horticultural (Tian et al., 2011; Campiglia et al., 2015) and agronomic crops (Lu et al., 2000) and should also be considered in high tunnels.

Conclusions

As high tunnel production continues to increase in the U.S., the need for soil health management practices that can be adopted into these systems is critical. To our knowledge, this report is the first study to evaluate summer and winter cover crop performance within high tunnels and describes the impact of cover crops on soil properties. Overall, using cover crops in high tunnels resulted in an increase in soil organic matter, total carbon, and total nitrogen during peak time points after cover crop termination. In the summer experiments, sorghum-sudangrass produced the most biomass, resulting in the highest available nitrogen contribution to soil tillage layer post cover crop termination. Similarly, buckwheat and cowpeas were high biomass producers of the summer cover crops tested. In the winter experiments, rye produced the highest biomass. However, winter cover crops had inconsistent growth patterns across the two years making winter cover crop recommendations more difficult. It is worth noting that hairy vetch did not accumulate very much biomass in either year. In the summer and winter cover crop experiments, the best performing cover crops contributed at least 90 lbs N/acre, which is sufficient for many vegetable crops. The timing of nitrogen release from residues vary based on complex soil properties, cover crop species, and growing season (Brady and Weil, 2004). Our data suggests that winter cover crops release nitrogen within four weeks of termination, while summer cover crops release nitrogen within two weeks of termination in high tunnels. Interestingly, we were able to observe increases in soil carbon and nitrogen as a result of utilizing cover crops in the high tunnel whereas these effects may take longer to document in the open field. As we continue to develop sustainable and productive food production systems, the use of cover crops will continue to be important. The findings of this work suggest that by implementing cover crops, high tunnel growers may be able to directly impact their soil in a positive way and help overcome the deleterious effects of intensive cultivation in regard to soil properties.

Table 2-1: Average weather data in high tunnel 2018 and 2019[z]

Month	Average Soil Temperature (F°)	Average Air Temperature (F°)	Air Relative Humidity (%)	Soil Moisture (%)
November[y]	43	34	80	30
December	41	35	81	28
January	38	30	82	25
February	38	30	81	24
March	48	41	73	23
April	62	58	68	21
May	65	60	85	20
June[x]	76	76	70	21
June	76	76	71	20
July	83	79	77	21
August	78	78	84	25
September	78	78	84	25

[z]Weather data during winter and summer cover crop growth was collected using HOBOware weather stations (Onset Computer Corporation, Bourne, MA) which recorded average soil temperature (F°), average air temperature (F°), air relative humidity (%), and soil moisture content (%).

[y]The month of November is when weather data for winter cover crops started. Cover crops were terminated in May

[x]June is when summer cover crops were planted and weather data was recorded. Summer cover crops were terminated early September in 2018 and early August in 2019.

Table 2-2: Summer and winter study cover crop treatments, seeding rates, and abbreviations[z].

Treatment	Cover Crop	Rate (lbs./acre)	Cover Crop	Rate (lbs./acre)
		Winter		
BC	Bare Control	0		
T	Triticale	100		
V	Hairy Vetch	45		
W	Wheat	150		
R	Rye	150		
T+V	Triticale	67	Hairy vetch	30
W+V	Wheat	100	Hairy Vetch	30
R+V	Rye	100	Hairy Vetch	30
		Summer		
BC	Bare Control	0		
B	Buckwheat	90		
C	Cowpea	140		
M	Japanese Millet	30		
SS	Sorghum-Sudangrass	50		
B+C	Buckwheat	60	Cowpea	100
M+C	Japanese Millet	20	Cowpea	100
SS+C	Sorghum-Sudangrass	33	Cowpea	100

Table 2-3: ANOVA table winter cover crop study

Factors	Dry Biomass (lbs/acre)	Available N (lbs/acre)	Soil Total Carbon %	Soil Total Nitrogen %	Soil Organic Matter
Day (D)	---	---	<0.0001	<0.0001	<0.01
Treatment (T)	<0.0001	<0.001	<0.0001	<0.0001	<0.0001
Year (Y)	<0.01	<0.0001	<0.0001	<0.0001	<0.0001
D x T	---	---	<0.0001	<0.0001	<0.0001
D x Y	---	---	<0.0001	<0.0001	<0.0001
Y x T	NS	NS	<0.0001	<0.0001	<0.01
D x T x Y	---	---	<0.0001	<0.0001	<0.0001

Table 2-4: Biomass and plant height of winter cover crops at termination grown alone and in mixtures in a high tunnel in Olathe, KS

Treatment[z]	2018				2019			
	Biomass[y] (lbs/acre)		Height Measurement[y] (in.)		Biomass (lbs/acre)		Height Measurement (in.)	
Bare Control	0	c[x]	0.00	c[x]	0	c	0	c
Triticale	5481	ab	39	b	89	c	23	ab
Hairy Vetch	92	c	9	c	0	c	11	bc
Wheat	6341	ab	31	b	864	abc	23	ab
Rye	7641	ab	57	a	2187	a	32	a
Triticale and Vetch	8617	a	39	b	0	c	15	abc
Wheat and Vetch	4506	b	32	b	793	bc	26	ab
Rye and Vetch	8756	a	56	a	1965	ab	30	a
P-value	<0.0001		<0.0001		<0.0001		<0.0001	

[z]The experiment was arranged in a split plot randomized complete block design with the main plot factor as the presence/absence of legumes (hairy vetch) and the subplot factor were the cover crop species/mixtures. There were 4 blocks in the experiment, yielding 4 replications of each treatment. There were differences in cover cropping biomass yields by year (P=0.0001).

[y]Cover crops were planted on 19 October 2017 and 15 October 2018 and terminated on 9 May 2018 and 9 May 2019. Cover crops were grown under a quonset high tunnel with average temperatures ranging from 34°F to 60°F. Biomass samples collected using a 0.1 m quadrant for each plot were dried. One-way analysis of variance (ANOVA) was used to evaluate cover crop biomass by treatment for each year. Treatment effects on cover crop biomass yield were significant in both 2018 ($P < 0.0001$) and 2019 ($P < 0.0001$). Cover crop height was measured at cover crop termination.

[x] Values followed by the same letter in the same column are not significantly different according to a protected Tukey method to compare LSDs with α=0.05

Table 2-5: Mean available nitrogen of winter cover crops at termination in a high tunnel in Olathe, KS in 2018 and 2019

	2018		2019	
Treatment	Available N[z] (lbs N/acre)		Available N (lbs N/acre)	
Bare Control	0.00	c[y]	0.00	c
Triticale	41.55	abc	1.05	c
Hairy Vetch	1.68	bc	0.00	c
Wheat	50.59	abc	6.86	bc
Rye	100.98	a	18.58	a
Triticale and Vetch	80.91	a	0.00	c
Wheat and Vetch	43.08	abc	6.76	bc
Rye and Vetch	69.42	ab	16.53	ab
P-value	<0.001		<0.0001	

[z]Plant available nitrogen (PAN) estimates were calculated using a PAN calculator (Buric, 2012). There were significant differences in mean available N by treatment based on sampling years *(P <0.0001)*. Based on ANOVA, there was a treatment effect on available N in both sampling years. In 2018, plant available N by treatment *(P=0.0004)* and in 2019 *(P<0.0001)*.

[y] Different letters show significant differences between values when using the Tukey method to compare LSDs with α=0.05.

Table 2-6: ANOVA table summer cover crop study

Factors	Dry Biomass (lbs/acre)	Available N (lbs/acre)	Soil Total Carbon %	Soil Total Nitrogen %	Soil Organic Matter
Day (D)	---	---	<0.0001	<0.0001	<0.0001
Treatment (T)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Year (Y)	<0.05	NS	<0.0001	<0.0001	NS
D x T	---	---	<0.0001	<0.0001	<0.0001
D x Y	---	---	<0.0001	<0.0001	<0.0001
Y x T	NS	NS	<0.01	<0.0001	<0.0001
D x T x Y	---	---	<0.0001	<0.0001	<0.0001

Table 2-7: Biomass and plant height at termination of summer cover crops grown alone and in mixtures in a high tunnel in Olathe, KS

	2018				2019			
Treatment[z]	Biomass[y] (lbs/acre)		Height[y] (in.)		Biomass (lbs/acre)		Height (in.)	
Bare Control	0	c[x]	0	d[x]	0	b	0	c
Buckwheat	1571	c	34	c	3112	b	28	abc
Buckwheat and Cowpea	3796	c	39	c	4993	b	36	abc
Cowpea	6016	bc	38	c	5435	ab	37	abc
Japanese Millet	1472	c	32	c	6480	ab	27	bc
Japanese Millet and Cowpea	4613	c	39	c	6689	b	35	abc
Sorghum-Sudan	21273	a	78	a	11009	a	63	a
Sorghum-Sudan and Cowpea	20726	ab	54	b	6155	b	53	ab
P-value	<0.0001		<0.0001		<0.001		<0.0001	

[z]The experiment was arranged in a split plot randomized complete block design with the main plot factor as the presence/absence of legumes (cowpea) and the subplot factor were the cover crop species/mixtures. There were 4 blocks in the experiment, yielding 4 replications of each treatment. There were differences in cover cropping biomass yields by year (P= 0.0349).

[y]Cover crops were planted on 19 June in 2018 and 11 June 11 in 2019 and terminated on 4 Sept 2018 and 6 Aug 2019. Cover crops were grown under a quonset style high tunnel with average temperatures ranging from 76°F to 79°F. Biomass samples were collected using a 0.1 m quadrant for each plot and were dried. One-way analysis of variance (ANOVA) was used to evaluate cover crop biomass by treatment for each year. Treatment effects on cover crop biomass yield were significant in both 2018 ($P < 0.0001$) and 2019 ($P < 0.001$). Cover crop height was measured at cover crop termination.

[x]Values followed by the same letter in the same column are not significantly different according to a protected Tukey method to compare LSDs with α=0.05

Table 2-8: Mean available nitrogen of summer cover crops at termination in a high tunnel in Olathe, KS in 2018 and 2019

	2018		2019
Treatment	Available N[z] (lbs N/acre)		Available N (lbs N/acre)
Bare Control	0.00	d[y]	0.00
Buckwheat	40.82	abcd	32.92
Cowpea	84.45	ab	82.78
Japanese Millet	6.68	bcd	61.07
Sorghum-Sudan	94.76	a	104.75
Buckwheat and Cowpea	3.51	cd	11.14
Japanese Millet and Cowpea	26.48	bcd	51.79
Sorghum-Sudan and Cowpea	79.66	abc	48.50
P-value	<0.001		NS

[z]Plant available nitrogen (PAN) estimates were calculated using a PAN calculator (Buric, 2012). There were no significant differences in mean available N by treatment based on sampling years *(P=0.3821)*. Based on ANOVA, there was a treatment effect on available N year in 2018 *(P=0.0005)* but not in 2019 *(P=0.0697)* at the α=0.05 level

[y]Different letters show significant differences between values when using the Tukey method to compare LSDs with α=0.05.

Table 2-90: Soil N, C, and OM of winter high tunnel cover crop treatments at various time points after cover crop termination

	2018						2019					
	Total N[x] (%)		Total C (%)		OM (%)		Total N (%)		Total C (%)		OM (%)	
Treatments[z]	**Baseline (Pre-plant)**											
Bare Control	0.22	a[w]	2.36	bc	4.20	a	0.21	de	2.42	b	3.88	c
Rye	0.21	bc	2.41	a	4.20	a	0.21	de	2.48	a	3.98	bc
Rye and Vetch	0.21	abc	2.41	a	4.23	a	0.22	a	2.49	a	4.05	ab
Triticale	0.20	d	2.33	cd	4.10	b	0.20	e	2.40	b	3.95	bc
Triticale and Vetch	0.21	ab	2.41	a	4.23	a	0.21	abc	2.50	a	4.10	a
Vetch	0.20	c	2.39	ab	4.18	a	0.21	bcd	2.42	b	3.90	c
Wheat	0.21	bc	2.30	d	4.03	c	0.21	cd	2.39	b	3.93	c
Wheat and Vetch	0.21	ab	2.40	ab	4.18	a	0.21	ab	2.48	a	3.93	c
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
	Day 0 (Termination)[y]											
Bare Control	0.22	b	2.36	c	4.15	cd	0.21	ab	2.46	b	4.10	bc
Rye	0.22	b	2.45	a	4.30	ab	0.20	c	2.54	a	4.13	ab
Rye and Vetch	0.21	b	2.41	b	4.33	a	0.21	a	2.55	a	4.20	a
Triticale	0.22	b	2.38	bc	4.15	cd	0.20	bc	2.46	b	4.03	c
Triticale and Vetch	0.22	b	2.40	b	4.28	ab	0.21	a	2.49	b	4.05	bc
Vetch	0.22	b	2.41	b	4.23	bc	0.19	d	2.40	c	4.03	c
Wheat	0.22	b	2.36	c	4.10	d	0.20	bc	2.46	b	4.05	bc
Wheat and Vetch	0.24	a	2.42	b	4.30	ab	0.21	ab	2.47	b	4.10	bc
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
	Day 28											
Bare Control	0.22	a	2.50	a	4.15	ab	0.21	d	2.54	abc	4.18	bc
Rye	0.21	b	2.50	a	4.18	a	0.23	ab	2.54	abc	4.13	c
Rye and Vetch	0.20	b	2.48	a	4.18	a	0.22	cd	2.60	a	4.23	b
Triticale	0.20	b	2.47	abc	4.15	ab	0.23	b	2.54	abc	4.20	b
Triticale and Vetch	0.21	b	2.44	bc	4.13	ab	0.22	bc	2.52	bc	4.20	b
Vetch	0.20	b	2.49	ab	4.18	a	0.22	bc	2.53	bc	4.13	c
Wheat	0.20	b	2.43	c	4.08	b	0.24	a	2.57	ab	4.13	c
Wheat and Vetch	0.22	a	2.45	abc	4.10	ab	0.22	bc	2.50	c	4.35	a
P-value	<0.0001		<0.0001		<0.01		<0.0001		<0.0001		<0.0001	
	Day 56											
Bare Control	0.21	ab	2.38	bc	--	--	0.21	d	2.41	c	3.93	
Rye	0.20	c	2.44	a	--	--	0.23	a	2.46	ab	3.98	
Rye and Vetch	0.21	ab	2.41	abc	--	--	0.22	b	2.51	a	4.03	
Triticale	0.21	bc	2.37	c	--	--	0.22	bc	2.44	bc	3.95	
Triticale and Vetch	0.21	ab	2.42	ab	--	--	0.22	b	2.42	bc	3.95	
Vetch	0.21	a	2.44	a	--	--	0.22	b	2.45	bc	4.00	
Wheat	0.21	ab	2.38	bc	--	--	0.22	b	2.44	bc	4.00	
Wheat and Vetch	0.21	ab	2.43	a	--	--	0.21	cd	2.44	bc	4.00	
P-value	<0.0001		<0.0001				<0.0001		<0.0001		NS	

[z]Randomized soil samples were collected from each cover crop treatment plot using a soil probe at three time points from cover crop termination onward.

[y]Plots containing cover crops were terminated using hand tools on May 9, 2018 and May 9, 2019 (Day 0) and were tilled two weeks later.

[x]Soil total nitrogen (N), total carbon (C), and organic matter (OM) are reported as weighted percentage from soil samples and were analyzed using one-way analysis of means. No organic matter data was collected on Day 56 of 2018

[w] Different letters show significant differences between values when using the Tukey method to compare LSDs independently of day with α=0.05

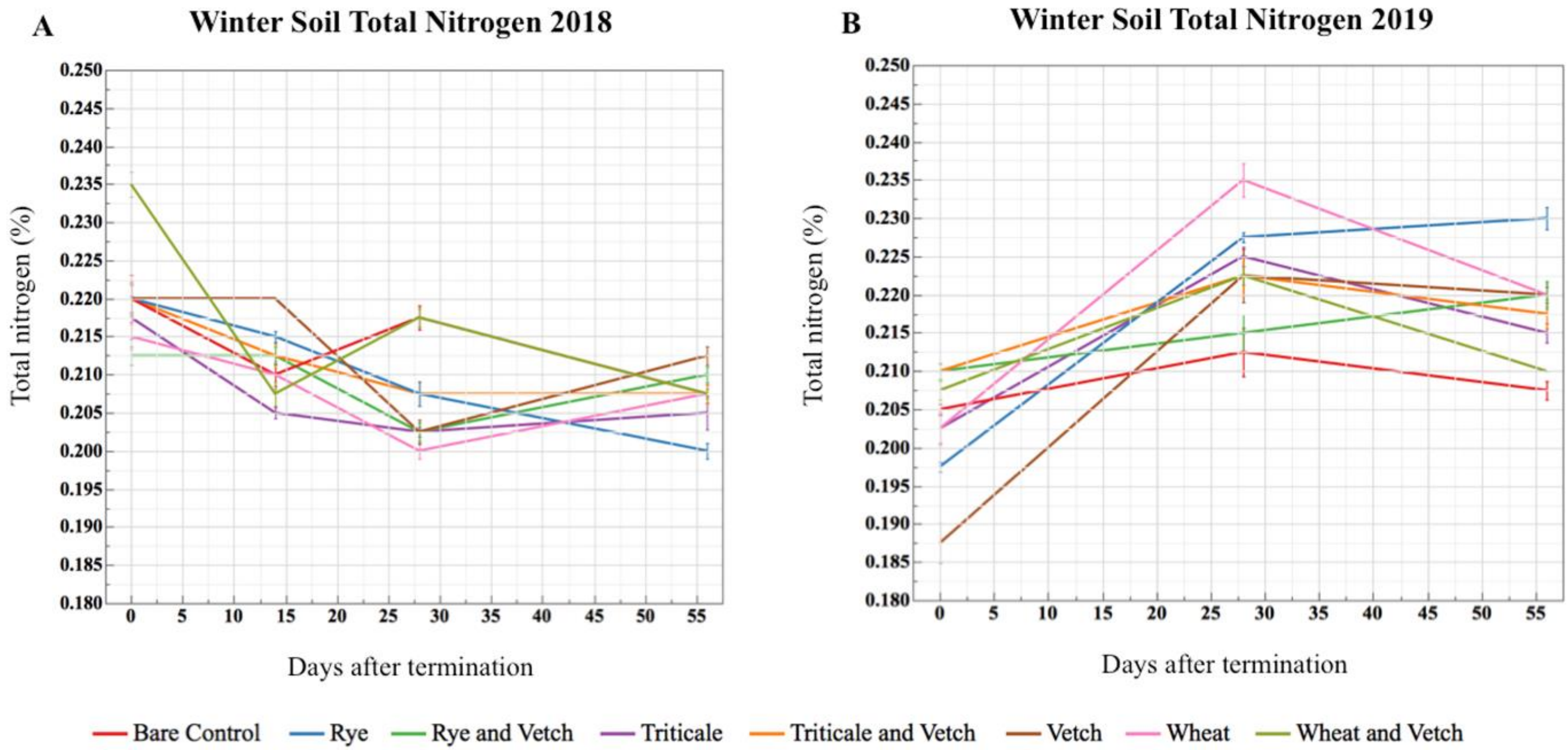

Figure 2-1:Trend of fluctuations in total soil nitrogen days after winter cover crop termination (A) mean total soil nitrogen for year one of winter cover crops *(P<0.0001)*. Crops were planted in October 2017 and terminated (0 days after termination) on May 9, 2018 (B) mean total soil nitrogen for year two of overwintering cover crops *(P<0.0001)*. Crops planted in October 2018 and terminated (0 days after termination) on May 9, 2019. Each error bar is constructed using 1 standard error from the mean.

Table 2-10: Soil total N, C, and OM of summer high tunnel cover crop treatments at various time points after cover crop termination

	2018						2019					
	Total N[x] (%)		Total C (%)		OM (%)		Total N (%)		Total C (%)		OM (%)	
Treatments[z]	**Baseline (Pre-plant)**											
Bare Control	0.22	a[w]	2.39	c	4.05	c	0.23	b	2.59	ab	4.15	b
Buckwheat	0.22	a	2.45	a	4.10	bc	0.23	b	2.57	ab	4.20	b
Buckwheat and Cowpea	0.20	c	2.42	abc	4.10	bc	0.22	bc	2.55	b	4.13	b
Cowpea	0.22	a	2.42	abc	4.10	bc	0.22	b	2.61	a	4.15	b
Japanese Millet	0.21	ab	2.40	bc	4.08	bc	0.22	d	2.49	c	4.20	b
Japanese Millet and Cowpea	0.20	bc	2.44	ab	4.10	bc	0.23	a	2.57	ab	4.18	b
Sorghum-sudangrass	0.22	a	2.46	a	4.18	a	0.22	cd	2.57	ab	4.33	a
Sorghum-sudangrass and Cowpea	0.21	ab	2.45	abc	4.13	ab	0.23	bc	2.58	ab	4.15	b
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
	Day 0 (Termination)[y]											
Bare Control	0.20	ab	2.40	c	4.13	ab	0.22	cd	2.48	c	3.92	
Buckwheat	0.20	ab	2.44	abc	4.10	ab	0.22	d	2.56	a	4.03	
Buckwheat and Cowpea	0.21	a	2.42	b	4.05	b	0.22	bcd	2.54	ab	4.00	
Cowpea	0.21	a	2.43	abc	4.08	ab	0.23	abc	2.53	ab	4.00	
Japanese Millet	0.20	b	2.41	cd	4.15	a	0.21	ab	2.54	ab	4.00	
Japanese Millet and Cowpea	0.20	ab	2.45	ab	4.13	ab	0.23	a	2.56	a	3.93	
Sorghum-sudangrass	0.20	ab	2.46	bcd	4.15	a	0.23	ab	2.53	ab	4.05	
Sorghum-sudangrass and Cowpea	0.21	a	2.43	bcd	4.15	a	0.23	ab	2.51	bc	3.93	
P-value	<0.001		<0.0001		<0.001		<0.0001		<0.0001		NS	
	Day 14											
Bare Control	0.21	a	2.45	cd	4.00	b	0.21	d	2.50	c	3.98	d
Buckwheat	0.21	a	2.52	a	4.27	a	0.22	cd	2.61	a	4.10	b
Buckwheat and Cowpea	0.21	a	2.49	ab	4.20	ab	0.22	bcd	2.61	a	4.15	a
Cowpea	0.19	c	2.43	d	4.17	ab	0.22	bc	2.58	ab	4.03	c
Japanese Millet	0.20	b	2.43	d	4.04	b	0.22	ab	2.55	b	4.05	c
Japanese Millet and Cowpea	0.20	bc	2.47	bc	4.16	ab	0.23	a	2.60	a	4.10	b
Sorghum-sudangrass	0.21	a	2.52	a	4.20	b	0.21	cd	2.60	a	4.10	b
Sorghum-sudangrass and Cowpea	0.20	c	2.43	d	4.13	ab	0.22	cd	2.55	b	4.05	c
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	
	Day 56											
Bare Control	0.21	b	2.43	d	4.05	bc	0.21	d	2.51	e	4.08	c
Buckwheat	0.22	ab	2.52	a	4.12	a	0.22	bc	2.54	cde	4.15	bc
Buckwheat and Cowpea	0.23	a	2.53	a	4.08	abc	0.24	a	2.61	a	4.25	a
Cowpea	0.23	ab	2.47	bc	4.10	abc	0.22	bc	2.56	bcd	4.13	bc
Japanese Millet	0.22	b	2.45	cd	4.03	c	0.22	c	2.57	abcd	4.15	bc
Japanese Millet and Cowpea	0.21	b	2.50	ab	4.00	c	0.21	d	2.54	de	4.10	bc
Sorghum-sudangrass	0.22	ab	2.52	a	4.15	ab	0.23	b	2.59	ab	4.18	ab
Sorghum-sudangrass and Cowpea	0.22	ab	2.45	cd	4.03	c	0.23	bc	2.59	abc	4.14	bc
P-value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

[z]Randomized soil samples were collected using a soil probe at three time points from cover crop termination onward.

[y]Plots containing cover crops were terminated using hand tools on September 4, 2018 and August 6, 2019 (Day 0) and were tilled two weeks later.

[x]Soil nutrients are reported as weighted percentage from randomized soil samples. Data was analyzed using one-way analysis of means.

[w]Different letters show significant differences between values when using the Tukey method to compare LSDs independently of day with α=0.05.

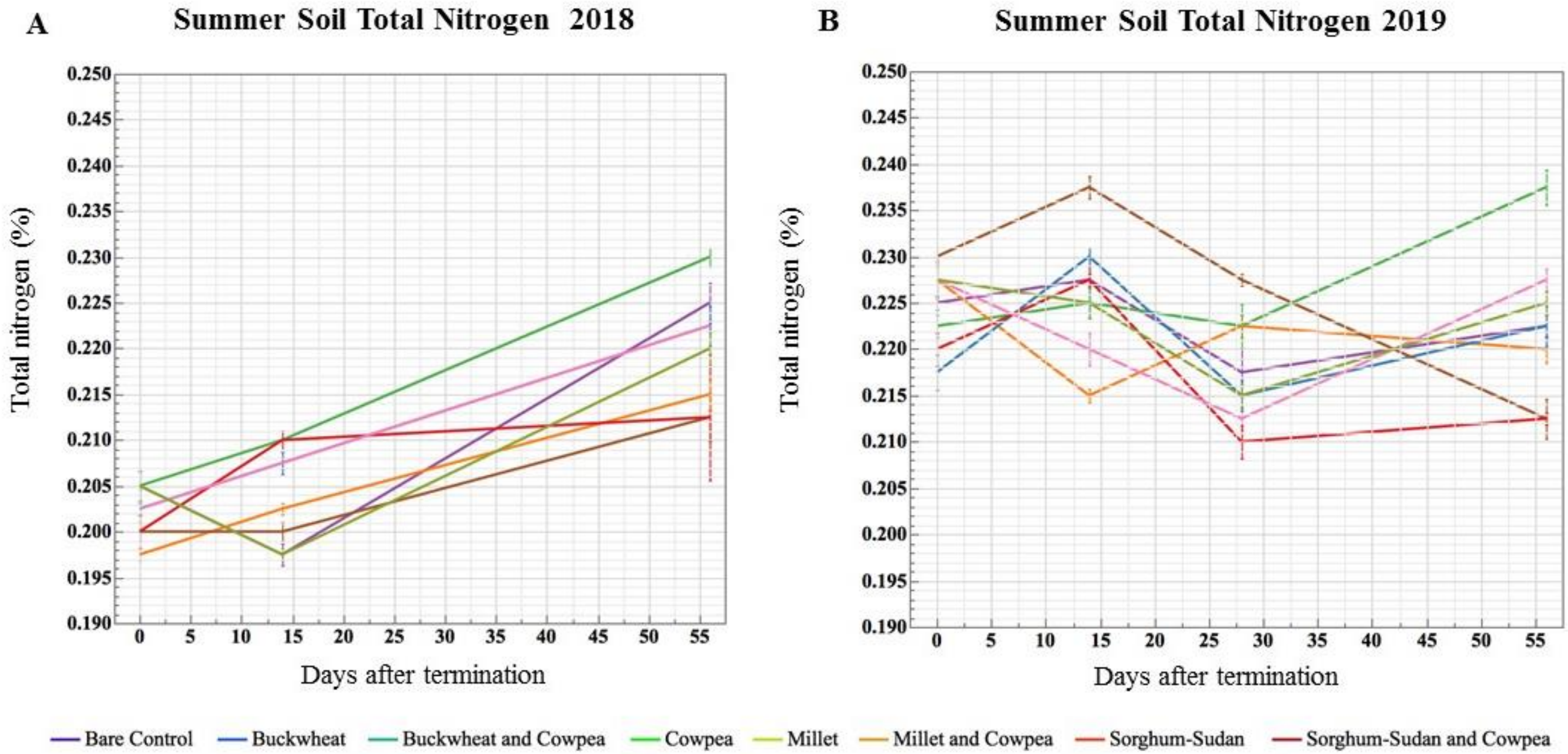

Figure 2-2:Trend of fluctuations in total soil nitrogen days after summer cover crop termination (A) mean total soil nitrogen for year one of summer cover crops by treatment *(P<0.0001)*. Crops were planted in June 2018 and terminated (0 days after termination) on September 4, 2018 (B) mean total soil nitrogen for year two of summer cover crops by treatment *(P<0.0001)*. Crops planted in June 2018 and terminated (0 days after termination) on August 6, 2019. Each error bar is constructed using 1 standard error from the mean.

Chapter 3- Belowground arthropods associated with cover crops grown in high tunnels

Abstract

Cover cropping is used to improve soil health in open-field agricultural production systems. Cover crops may also be integrated into high tunnel crop rotations to add organic matter and improve soil properties. In this study, the effects of cover crops on belowground arthropods was investigated. Winter and summer cover crops were used in experiments and the abundance of belowground arthropods was determined after termination of the cover crops. There were eight treatments during the winter and summer experiments conducted in a split-plot randomized completed block design with four replications per treatment. At cover crop termination (Day 0) and three time points afterward (Days 14, 28, and 56 post-termination), 96 g soil samples were collected to quantify soil organic matter, total carbon, total nitrogen, and soil water content. Additional soil samples were collected to determine the abundance of belowground arthropods using sieves and a lighted Berlese funnel system. Generalized additive models were used to predict arthropod abundance based on continuous and categorical variables (soil water content, organic matter, total nitrogen and total carbon). Mites *(Arachnida)* were the predominant belowground arthropods in the study and an increase in total carbon was associated with higher arachnid numbers in the summer experiment. During the summer cover crop experiment, higher organic matter post-termination predicted higher mite numbers whereas in the winter were lower mite numbers. Mite abundance in the study also varied by cover crop type in the summer experiment with the buckwheat and cowpea treatment having the most mites (0.82 mites per 96 g of soil). Soil water content and soil total nitrogen were not associated with mite abundance. Our

results indicate that cover crops may impact soil mite abundance. As the use of cover crops in high tunnels the abundance and types of arthropods in the soil may be altered.

Introduction

High tunnels (or 'hoophouses') are semi-permanent, moveable or temporary structures constructed of a metal, wooden or polyvinylchloride (PVC) frame with a plastic film covering (Carey et al., 2009; Knewtson et al., 2012). Throughout the United States, there has been an increase in using high tunnels for cool-season crops like leafy greens and warm-season crops such as tomato (*Solanum lycopersicum*) (Carey et al., 2009). The high tunnel microclimate can extend the growing season by warming soils, and allowing growers to produce crops year-round (Conner et al., 2009; Lamont, 2009; Rader and Karlsson, 2006). Early warming of soil in spring and into the fall makes the high tunnel microclimate favorable for crop growth (Lamont, 2009). High tunnels can also reduce damage from wind, air temperature, light intensity, and moisture (rain events) during the growing season (Wittwer and Castilla, 1995).

Soil is vital to the function of terrestrial ecosystems (Pankhurst et al., 1997). Despite the benefits of high tunnels in regards to productivity, production practices may not be ideal for sustaining or improving soil health. Growers typically produce crops in high tunnels intensively, with multiple crops grown each year with few crop rotation intervals (Carey et al., 2009). Intensive cultivation can lead to soil degradation (Norris and Congreves, 2018). Production practices that negatively affect soil health include: short crop rotations, over-fertilization, and frequent tillage (Pereira et al., 2018). Growers using high tunnels typically till after each cropping cycle, removing crop residues, and then plant a subsequent cash crop (Waterer, 2003). This practice may be repeated multiple times per year, as the microclimate in high tunnels allows for year-round production (Lamont, 2009).

Soil provides a habitat for a diversity of organisms (Ferris and Tuomisto, 2015). Some organisms are essential in the provisioning of food and fiber (Pereira et al., 2018). Soil organisms such as collembola (springtails), mites, bacteria, and fungi are considered ecosystem engineers because they alter soil physical properties and stabilize soil by forming microaggregates (Pereira et al., 2018; Benckiser, 1997). Belowground arthropods, including decomposers, fungal-feeders, and shredders, transfer energy through the food chain in the soil food web (Price et al., 2011; Pearsons and Tooker, 2017; United States Natural Resources Conservation Service., 2000). Arthropods and earthworms are litter transformers that fragment and shred plant residues that are decomposed through microbial activity (Culliney, 2013; United States Natural Resources Conservation Service., 2000).

However, intensive agriculture practices such as frequent tillage and limited crop rotations can affect belowground arthropod abundance and diversity (Benckiser, 1997). Intensive tillage causes physical displacement of soil belowground arthropods and plant residues after tillage can alter soil moisture and microbial growth (Benckiser, 1997). Nonetheless, conflicting information exists on belowground arthropod abundance in no-till soils versus tilled soils (Edwards and Lofty, 1977; Benckiser, 1997). For instance, reports indicate that intensive tillage negatively affects the number of mites and springtail species (Benckiser, 1997; Bund, 1970). Other studies have shown that carabids and mites are present in higher numbers in no-till systems (House, 1989; House and Parmelee, 1985). Long-term tillage increases the abundance of springtails and mites in the upper 5 to 15 cm of soil, and tilling cover crop residues into the soil results in a higher abundance of arthropod species during winter (Benckiser, 1997). Crop rotation can negatively or positively affect plant-insect interactions (Benckiser, 1997). For instance, collembola prefer wheat (*T. aestivum*) and barley (*Hordeum vulgare*) crops over sugar beet (*Beta* *vulgaris*) and other root and tuber crops, resulting in higher abundance in wheat and barley stands (Benckiser, 1997). Likewise, belowground arthropods show a preference for legume cover crop residues over grasses (House and Alzugaray, 1989).

The use of cover crops may improve soil health (Kim et al., 2013; Tribouillois et al., 2016; Belfry et al., 2017) in high tunnels (Skinner et al., Chptr 2). Replacing fallow periods with cover crops may help recover soil nitrogen after termination of cash crops by uptaking soil nitrogen and storing it in plant parts (Tonitto et al., 2006). Cover crops may also protect topsoil through mechanical action of the root system (Veiga et al., 2017). Planting cover crops such as red clover (*Trifolium pretense*) or radish (*Raphanus sativus*) can alleviate soil compaction due to deep rooting patterns (Buric, 2012; Parvatha, 2016; Rivers et al., 2018). Grass cover crop species such as cereal rye (*Secale cereale*) and wheat may establish roots up to three feet deep in one cropping season (Buric, 2012). These roots increase soil nutrient reserves and provide an environment that may support arthropod communities (Parvatha, 2016; Rivers et al., 2018). Quintanilla-Tornel et al. (2016) reported that minimum-tillage sunn hemp (*Crotalaria juncea*) plots had higher numbers of spiders than conventionally-tilled and control plots. Planting cowpea (*Vigna unguiculata*) and buckwheat (*Fagopyrum esculentum*) cover crops into vegetable crop rotations attracts arthropods due to the presence of flowers and nectar provisions (Quintanilla-Tornel et al., 2016). Studies have shown that cover crops such as sunn hemp increase the soil food web structure and complexity through increasing the abundance of fungivorous nematodes (Leslie et al., 2017; Quintanilla-Tornel et al., 2016; Wang, K.-H et al., 2011a; Wang, K-H et al., 2011b). The effects of cover crop mixtures on arthropod communities may be cover crop species and season specific (Rivers et al., 2018). Nonetheless, indices of soil species diversity are used to make inferences about soil ecosystem stability and resilience (Ferris and Tuomisto, 2015).

Belowground arthropods (insects and mites) are sensitive to disturbances and changes in soil conditions (water content/moisture, texture, pH, and temperature), allowing them to serve as indicators of ecosystem change (Mattoni et al., 2000; Kremen et al., 1993)

Soil characteristics that favor belowground arthropods are often altered by management practices (Benckiser, 1997). Therefore, promoting conservation and accumulation of carbon, water, and nutrients is important in sustaining belowground arthropod populations and food production (Pereira et al., 2018; Benckiser, 1997). Currently, there are recommended management strategies associated with agricultural systems in open fields, which can increase the sustainability of food production. However, there are no reports associated with the dynamics of belowground arthropod abundance and cover crop use in high tunnel production systems. Therefore, our research objectives were to: 1) determine the types of belowground arthropods in a high tunnel system when using winter and summer cover crops 2) identify soil properties (percentages of soil water content, organic matter, soil total nitrogen, and soil total carbon) that affect belowground arthropod populations in a high tunnel system 3) and assess the impact of winter and summer cover crops on belowground abundance using predictive modeling.

Materials and Methods

A detailed account of the materials and methods used for general cultivation, microclimate monitoring, and cover crop performance are in Skinner et. al, (Chptr 2).

Experiments associated with belowground arthropods were conducted simultaneously with the summer and winter cover crop experiments using similar methods. One experiment assessed belowground arthropod abundance after termination of a winter-hardy cover crop and the second experiment evaluated arthropod abundance after termination of summer cover crops.

Experiments were conducted from 2017-2019 in a high tunnel 200 ft. long and 15 ft. wide used for vegetable research for over 10 years. The two experiments were conducted at the Olathe Horticulture Center in Olathe, KS (38.884347 N, 94.993426 W). The high tunnel was managed according to National Organic Program (NOP) standards. Cantaloupe (*Cucumis melo*) was grown during the 2017 cropping season. Each experiment utilized a 51 ft. x 24 ft. area of the high tunnel with the summer cover crop experiment on the north end, and the winter cover crop experiment in the center of the tunnel. The experiments were set up as a split-plot randomized complete block design with presence or absence of legumes as the main plot factor and the subplot factor was the variety of non-leguminous crops used within the plots. The 'cover crop type' treatments consisted of four replications divided by 18 in. horizontal aisles and 2 ft. vertical aisles. Each treatment was managed in 4 x 5 ft. plots. Seven days after termination of the cover crops, each experimental plot was tilled using a two-wheel tractor tiller (BCS Model 732, BCS America, Texas). Fourteen days after cover crop termination, cash crops were planted to simulate a farmer's production schedule when utilizing cover crop rotations in high tunnels.

For the summer cover crop experiment, in the first block, the treatments included: buckwheat, japanese millet (*Echinochloa esculenta*), sorghum-sudangrass (*Sorghum* × *drummondii*), and a weed-free control plot with the absence of a leguminous species as the main plot factor, and the different non-legume species as the subplot factor. In the second block (presence of leguminous species), four additional treatments were included: cowpea, buckwheat and cowpea, millet and cowpea, and sorghum-sudangrass and cowpea. For the winter experiment, the treatments included: cereal rye (*Secale cereale*), hard red winter wheat (*Triticum aestivum*), triticale (×*Triticosecale*), and a weed-free control plot. Treatments for the main factor (the presence of legumes) included: hairy vetch (*Vicia villosa*), rye and hairy vetch, hard red winter wheat and hairy vetch, and triticale and hairy vetch. The cover crop selections were selected based on hardiness and regional cover crop data (Buric, 2012).

Summer cover crops were grown in a kale (*Brassica oleracea)*---cover crop---smooth leaf hybrid spinach (*Spinacia oleracea)* rotation, once per year. In 2018, the summer cover crops were broadcast seeded on 19 June and terminated on 4 September. In 2019, cover crops were broadcast seeded on 11 June and terminated on 6 August. The winter cover crops were broadcast seeded on 19 October 2017 and 15 October 2018 and terminated on 9 May 2018 and 9 May 2019. At termination, biomass samples were collected using a 0.1 m square quadrat (Parr et al., 2011). The quadrat was held in place on the ground and shears were used to cut the biomass within the quadrat at ground level (only aboveground plant parts were collected) (Parr et al., 2011). Samples (n=32) from each plot were dried using a Grieve SC-400 forced air dryer at 65^{0}C (Parr et al., 2011).

After sampling was completed, all experimental plots were terminated using hand shears. Biomass was retained on respective plots and incorporated using a two-wheel tractor tiller (BCS Model 732; BCS America, Texas). All plots (n=32) were irrigated after termination to promote cover crop residue decomposition (Lee et al., 2014). Seven days after termination, the soil in each plot was tilled to prepare for cash crop planting and promote residue decomposition. Fourteen days after cover crop termination, bell peppers (*Capsicum annuum*) were transplanted into the plots (n=32).

Arthropod Recovery and Classification

Belowground arthropod sampling was conducted four times: 0, 14, 28, and 56 days after cover crop termination. Belowground arthropods were collected from the upper 3-in of the soil profile using a soil probe (Shakir and Ahmed, 2014). Soil cores were extracted from the probe and placed into a clean plastic bucket for each plot. Plant material was removed from the bucket and soil cores were gently mixed in the bucket. Approximately eight cores for a total of 128 g of soil were collected from each plot and were then placed into plastic bags and stored at 4^{o}C until processing for arthropod collection. In addition, 128 g of soil was collected to determine total carbon (C), total nitrogen (N), and organic matter (OM). Soil samples were collected using a soil probe from the center of each plot (n=32) and from the upper 6-inches of the soil profile (tillage depth) (Gál et al., 2007). After collection, soil samples (n=32) were transported to the Kansas State University Soil Testing Laboratory (Manhattan, KS) for soil nutrient analysis and OM content.

Ninety-six grams of the 128 g soil samples were used to collect arthropods, with the remaining soil used for gravimetric soil water content analysis. Arthropods were recovered from the soil using a two-step process. The first step involved using two sieves (sizes of 2 mm and 250 microns) to capture arthropods approximately 1/8 inch in length from the soil samples. Soil was removed from the bags and placed in a 4 mm sieve, which was gently agitated until soil was collected into a metal pan placed beneath the sieve, and arthropods were recovered from the top of the sieve mesh (Gorman et al., 2013). This procedure was repeated until no more arthropods were recovered.

The second step involved using a lighted Berlese funnel system with a tulle lining (Figure 3-1). This step was a modification of a funnel extraction method from Macfadyen (1961) and Pande and Berthet (1973). Tulle lining was used as mesh between the soil and the funnel opening. A four row bank of twenty-four 65W reflector flood 620 lumens light bulbs (Phillips, China) were placed 3-in. above the funnel opening for 48 hours to heat the soil samples and promote the movement of any remaining arthropods (less than 1/8 inches) into glass vials containing 70% isopropyl alcohol (Macfadyen, 1961; Pande and Berthet, 1973) (Figure 3-1).

Afterward, the arthropods recovered in the vials were identified using a Nikon SMZ1000 microscope (Nikon Metrology, Brighton, MI) then classified into families/orders. The number and classification of the belowground arthropods were recorded after the experiments were terminated. The number of mean arthropods recovered from the experiments were determined for each sampling day (0, 14, 28, 56) and the range of arthropods recovered at each sampling time was recorded. Using a 4-gram subsample of soil from the arthropod soil samples, gravimetric soil water content was determined by oven drying samples (n=32) at 105°C for 12 hours.

Statistical Analysis

Generalized additive models (GAM) were used to analyze the arthropod data (GAMs; Wood 2017). The GAM framework was chosen because the framework allows for selecting a probability distribution that matches response variables, linear effects of continuous and categorical predictor variables, as well as temporal effects associated with time. For the response variable, which was abundance associated with each belowground arthropod classification, a negative binomial distribution was selected, to model abundance because the response variable is restricted to non-negative integer values (i.e., 0, 1, 2,…, ∞), of which, there is no reasonable upper bound to assume for the counts. In addition, the negative binomial distribution was selected because a small-scale spatial aggregation (clustering) of individual arthropods was expected, which would result in overdispersion (Pielou 1969).

To explain variation in abundance among arthropod classifications, soil nitrogen, carbon, water content, and organic matter were considered continuous predictor variables. To understand the effects of the experimental treatments (i.e., cover crop type), the categorical predictor variable “cover crop type” was used, which indicated the type of cover crop present at the location where each count was obtained.

For the continuous predictor variables (soil nitrogen, carbon, soil water content, and organic matter) statistical significance was set at $P < 0.05$ for the null hypothesis testing the effect of the predictor variable on abundance equal to zero vs. the alternative hypothesis testing the effect is not equal to zero. Continuous predictor variables that had a $P > 0.05$ were not interpreted because the estimated magnitude and sign of the estimated effect was less certain. Finally, the categorical predictor variable “cover crop type” was determined to be statistically significant when $P < 0.05$ for the null hypothesis testing the estimated treatment effect on abundance equal to the weed-free control vs. the alternative hypothesis in which the control and treatment did not result in similar arthropod abundance.

To account for temporal dependence (autocorrelation) generated by the omitted predictor variables (e.g., temperature) and species-specific population dynamics a “smooth” effect of time was included (Hefley et al. 2017; Wood 2017). The GAM framework allowed for linear effects of covariates such as weather or land cover, as well as nonlinear effects captured by basis functions (e.g., time). Finally, the arthropod data was separated by season (summer and winter). However, the two-year data from the continuous predictors was not separated by year.

Results

Cover Crop Performance and Soil Data Overview

Results of the microclimate, cover crop biomass, available nitrogen, and soil N, OM and total C are presented in Chapter 2. Cover crop biomass production varied by treatment in both the winter and summer experiments. Among the winter cover crops, cereal rye had the highest biomass (average of 4,914 lbs/acre) compared to the other treatments in the winter experiment. In the summer cover crop experiment, sorghum-sudangrass had the highest biomass at 16,141 lbs/acre, and there were significant changes in soil properties based on day after cover crop termination.

In the winter cover crop experiments, the effect of cover crop treatment on soil water content was not significant. At termination (Day 0) in 2018, soil water content was between 8-10%, which was significantly lower *($P < 0.001$)* than the other sampling dates (Figure 3-2). In the summer experiment, there was an effect of day on soil water content.

Mite Abundance and Predictive Modeling

In the summer and winter cover crop experiments, six arthropod classifications were determined, which included five families and arachnid class (Table 3-1). The *arachnida* class (mites) had the highest abundance and constituted 86% (n=1,830) of the individuals recovered. Other arthropods recovered in the winter and summer experiments ranged from 0-14 arthropods across all sampling times (Table 3-1) In table 3-1 arthropod groups such as carabidae and collembola were not recovered in the summer of 2019 and dermaptera were not recovered in winter of 2019. Due to the low numbers in other arthropod classifications (Table 3-1), the analysis was conducted only on arachnids. The expected abundance model of arachnids (Figure 3-3) indicates the average abundance of belowground arthropods found in the 96 g soil samples. To determine how cover crops may have affected mites, expected abundance was modeled using the mean predictor variable values obtained during the study (2.5% soil nitrogen, 2.0% total soil carbon, 14.6% water content, and 4.1% organic matter). Each cover crop type used in the study was evaluated based on the mean predictor variables. Significance (p-values) of cover crop type on belowground mite abundance is shown in Figure 3-3, cover crop types that had a significant effect on belowground mite abundance was indicated by dashed lines.

Treatment effect of cover crop type on mite abundance was significant in both the summer and winter experiments. Mite abundance in the summer cover crop was highest in the barley and cowpea treatment. In the expected abundance model, mite abundance in the buckwheat and cowpea treatment would be approximately five times greater than the control treatment based on mite abundance under the soil N, C, and OM levels associated with the study. In the winter cover crop experiment, wheat and vetch, triticale, wheat, and triticale and vetch had lower abundance of mites (Figure 3-3). Suggesting that mite abundance for these four treatments would be an order of magnitude less than the control treatment.

Soil carbon and organic matter (continuous predictor variables) were statistically significant variables ($P < 0.05$). The GAM model was used to demonstrate how changes in the continuous predictor variables (predictor variables are adjustable) may affect mite abundance by treatment (Figure 3-4). Based on the model, for every 1% increase in soil organic matter in summer, mite abundance would increase by approximately 14 times (Figure 3-5). In winter for every 1% increase in soil carbon mite abundance would increase by approximately 255 times (Figure 3-5). For every 1% increase in soil organic matter arachnid abundance would decrease by approximately 74 times in winter (Figure 3-5). In both the summer and winter experiments changes in soil total nitrogen and soil water content did not influence soil arthropod abundance.

Discussion

This study focused on determining the effects of cover cropping on belowground arthropods in a high tunnel. Our hypothesis was that after cover crop termination, belowground arthropod abundance would increase based on cover crop treatment, soil water content, soil nitrogen, carbon, and organic matter. In the study, mites were more abundant than other belowground arthropods and abundance was associated with cover crop type, soil organic matter, and total soil carbon.

Arachnids (mites) are the primary group of belowground arthropods in agroecosystems (Bokhorst et al., 2014; Postma-Blaauw et al., 2012; Tigar and Osborne, 1997; Wiwatwitaya and Takeda, 2005). In our study, arachnids represented 86% of the arthropods recovered (n=1830). Mites are important in the decomposition of plant residues (Holmstrup et al., 2013). Mites feed on fungi and contribute to the fragmentation of plant residues (Faber, 1991; Seastedt, 1984; Verhoef and Brussard, 1990). Decomposition is a decrease in the mass of a substrate, which occurs through leaching of soluble constituents, catabolism or oxidation of organic matter, conversion of carbon into gases, water, and energy and physical breakdown of the substrate (Seastedt, 1984). When mites feed on microorganisms in plant debris, they fragment organic matter (Seastedt, 1984). Residue fragmentation is distinct from decomposition since mass is not lost, but important in decomposition (Seastedt, 1984). Some mites fragment plant debris and residues, which increases availability for microbial decomposition (Seastedt, 1984; United States Natural Resources Conservation Service, 2000). After fragmentation, mineralization occurs which includes decomposition, resulting in the release of organic compounds in an inorganic form for plant uptake takes place. Some mites also feed on fungal pathogens and phytopathogenic nematodes (Benckiser, 1997).

A limitation of the data reported was that mites were not identified to species. Mite species can differ depending on function thus there is no way to determine the contributions of mites to soil health in the study. Some mite species are predators, decomposers, or fungal feeders (mites responsible for nutrient release in soil for plant uptake) (United States Natural Resources

Conservation Service., 2000). Mites also differ in terms of residue fragmentation and may respond differently to changes in soil conditions (Maribie et al., 2011). However, our findings provide a snapshot of the class of arthropods that predominate in high tunnel soils.

In addition to mite abundance, other arthropods were also collected in the study, but at low numbers. Arthropod complexity is based on functionality and also diversity of species found in soils (United States Natural Resources Conservation Service., 2000). In agricultural systems, low complexity is common and can affect nutrient cycling and soil structure (United States Natural Resources Conservation Service., 2000). Agricultural soils can have up to 100 soil arthropod species per square foot whereas forest soils can have up to 25,000 many more species (United States Natural Resources Conservation Service., 2000). Recovering mostly mites from the high tunnel during the study may reveal a lack of complexity in the growing system. Complexity in the agroecosystems allows for diverse functional groups and more energy transfers than simple ecosystems (United States Natural Resources Conservation Service., 2000).

Cover Crop Type and Soil Properties

Cover cropping in the high tunnel resulted in an increase in soil organic matter, total soil carbon, and total nitrogen (Skinner et al., Chptr 2). In the summer cover crop experiment, the buckwheat and cowpea treatment had five times more mites than the control treatment. The buckwheat and cowpea treatment yielded between 3,000 and 4,000 lbs/acre, which was similar to the millet and cowpea, millet, and buckwheat treatments. Despite similar biomass yields in other treatments, the buckwheat and cowpea treatment had a higher abundance of mites than the other treatments in the summer cover crop experiment averaging 0.82 mites per 96 g of soil. Similar to other studies, it appears that crop type may influence mite abundance more than biomass alone (Robertson et al. 2012; Shakir and Ahmed, 2014), which may be related to crop type preferences

(Bokhorst et al., 2014; Maribie et al, 2011; Mollot et al, 2014). Preferences of soil mites have been reported in grassland, corn production, and forest systems (Benckiser, 1997; Maribie et al, 2011; Robertson et. al, 2012).

In the winter cover crops for 2018 and 2019, the wheat and vetch, triticale, wheat, and triticale and vetch treatments had fewer mites than the weed-free control. Future studies using winter cover crops are warranted because biomass yields can vary considerably among years (Brennan and Smith, 2005). In our study, wheat and vetch, triticale, wheat, triticale and vetch treatment biomass yields were different between 2018 and 2019, with less biomass (3,000 to 8,000 lbs/acre) in 2019 for all treatments. In the summer cover crop experiment biomass yields were significantly different between the two years but were comparable with open field experiments where the same cover crops were used. In the second year of the winter experiment, many plot's had similar biomass yields as the weed-free control, but there were no significant difference in mite abundance between the two years. This suggests that cover crop type may be associated with mite abundance, however, further investigations are needed to determine if this is due to mite habitat, feeding, or other preferences (Bokhorst et al., 2014; Maribie et al, 2011; Mollot et al, 2014).

Seasonal variations in belowground arthropod abundance may be associated with changes in climatic conditions (Shakir and Ahmed, 2014). In open field production systems, arthropod abundance is affected by drought and moisture (rain) variations (Shakir and Ahmed, 2014), with abundance higher in drier seasons than rainy seasons (Shakir and Ahmed, 2014). However, seasonality (summer versus winter) was not a factor that affected belowground arthropod abundance in our study. In our study, both years of winter cover cropping resulted in an increase in soil organic matter but a decrease in mite abundance.

The effects of soil properties on belowground soil arthropod abundance has been investigated. Miasto et al. (2017) found that agricultural soils have lower organic matter and water content than forest soils. Agricultural soils had lower organic matter due to intensive management practices such as short cropping rotations and removal of vegetation (Maisto et al., 2017). Soils with low organic matter and water content had lower arthropod density and diversity (Maisto et al., 2017). Shakir and Ahmed (2014) reported that diversity and abundance of mites increased as soil organic matter increased, which was similar in our summer experiments. In our expected abundance model, for every 1% increase in soil organic matter, mite abundance was expected to increase by approximately 14 times. However, in the winter experiments, mite abundance was reduced when soil organic matter increased. This finding is not consistent with other research studies (Khalil et al., 2016; Manwaring et al., 2018).

Soil Water Content (Moisture)

Studies investigating the relationship between belowground arthropod abundance and soil water content are not consistent. Some studies suggest soil water content is a reliable predictor of species abundance and richness in open field systems **(**Hawkins et al., 2003; Verdeny-Vilalta and Moya-Larano, 2014), and dry conditions alter animal interactions and arthropod physiology (Stenseth et al., 2002; Verdeny-Vilalta and Moya-Larano, 2014). Studies indicate that a higher abundance of belowground arthropods under low soil water levels are associated migration to more favorable soil conditions and physiological changes such as decreased water permeability of body parts (Ferguson, 2004; Verdeny-Vilalta and Moya-Larano, 2014).

In the first year of the winter experiments, preliminary results indicated that arthropod abundance was associated with soil water content in high tunnels $(P < 0.05)$. At cover crop termination, no belowground arthropods were recovered, and soil water content was between 8-

10%. Overhead irrigation was provided to enhance cover crop decomposition (Lee et al., 2014), and raised the soil water content (moisture) to about 18% by day 14 post cover crop termination. Consequently, belowground arthropods were recovered during the next sampling and thereafter. Holmstrup et al. (2013), recorded mite abundance during thirteen years of drought in heathland soils found that drought conditions did not significantly affect mite abundance. In addition, Shakir and Ahmed (2014) found that soil moisture did not affect mite abundance in fruit, grain, and fiber production systems, whereas mite abundance was negatively affected by low soil temperatures in winter. Similarly, soil moisture did not affect belowground arthropod abundance in the summer or winter cover crop experiments. High tunnels may protect belowground arthropods from cyclic changes in soil water content that occur in open field production systems (Lamont, 2005; Schmied et al., 2003). Although Shakir and Ahmed (2014) found an association between arthropod abundance and soil temperature, in our study soil temperature was not monitored in the winter and summer experiments. Therefore, soil temperature was not included in the analysis as a continuous predictor variable for belowground arthropod abundance.

Limitations

Despite variability in mite abundance based on cover crop type, we do not know if mite abundance post winter cover crop termination was affiliated with the quantity or quality of residues, or other factors not measured in the study such as changes in soil temperature or cash crop interaction (Bokhorst et al., 2014). Therefore, changes in soil temperature due to cover crops may help explain the differences in our study in regards to mite abundance among the treatments.

Nitrogen derived from cover crops are converted to nitrates in the soil and used by cash crops (Blanco-Canqui et al., 2012). However, nitrates are available when cover crop residues are decomposed. Our study did not measure residue decomposition nor quantify microbial biomass and diversity throughout cover crop decomposition. Mineralization is a complex process associated with fragmentation and decomposition by a variety of soil organisms. Therefore, future studies are needed to investigate mineralization and the organisms involved related to cover crop residues.

Conclusion

This study is the first to investigate belowground arthropod abundance in a high tunnel production system and determine the effect of cover crop species. In the study, mites were the most abundant arthropods. In the summer cover crop experiments, more mites were recovered from the buckwheat and cowpea treatment than the other treatments. In the winter cover crop experiments, wheat and vetch, triticale, wheat, and triticale and vetch treatments resulted in fewer mites, indicating that cover crop type may influence mite abundance. In the summer experiment, as soil organic matter increased, mite abundance also increased. However, in the winter experiment, as soil organic matter increased, mite abundance decreased. Therefore, the effects of organic matter on soil arthropod abundance is not clear. As such, more studies are needed to understand why decreases in mite abundance occur with increases in soil organic matter.

Despite studies in open field systems showing a positive correlation between soil water content and arthropod abundance, this was not be the case in high tunnels when dry soil conditions occur. Dry soil conditions at the start of the experiments may have resulted in unfavorable conditions for survival. We did not classify belowground arthropod families based on function or measure the impact of arthropods on cover crop decomposition. Therefore, we were not able to assess whether the mites were predators or fungivores, which may have indicated their function in the soil ecosystem. In the study, we did see low diversity of arthropod families in high tunnel systems which may affect soil ecosystem services. This study assessed the relationship between production practices and changes in arthropod abundance. In conclusion, soil management practices in high tunnels can affect arthropod abundance by cover crop type, soil carbon, and organic matter. Understanding how production practices in high tunnels can affect belowground arthropods will help develop best management practices for soil health in high tunnels.

Figure 3-1: Sixty-five watt lighted berlese funnel with tulle lining used to extract belowground arthropods from soil. Modified version of Macfadyen (1961) and Pande and Berthet (1973).

Table 3-1: Arthropod classifications associated with two-year study (2018 and 2019), season, day, mean number of arthropods recovered from 96 grams of soil, and range of arthropods recovered.

Season	Arthropod Classifications[Z]	Year	Sampling Day	Mean	Range
Winter	Arachnida	2018	Day 0	0	0
			Day 14	2.44	0-78
			Day 28	19.44	0-96
			Day 56	1.88	0-16
	Arachnida	2019	Day 0	3.78	0-69
			Day 14	0	0
			Day 28	5.34	0-28
			Day 56	0.38	0-2
Summer	Arachnida	2018	Day 0	6.28	0-26
			Day 14	3.28	0-78
			Day 28	1.84	0-14
			Day 56	0.41	0-4
	Arachnida	2019	Day 0	0.19	0-3
			Day 14	1.97	0-33
			Day 28	1.91	0-41
			Day 56	0.09	0-1
Winter	Carabidae	2018	Day 0	0	0
			Day 14	0	0
			Day 28	0.13	0-1
			Day 56	0.03	0-1
	Carabidae	2019	Day 0	0	0
			Day 14	0	0
			Day 28	0.09	0-1
			Day 56	0	0
Summer	Carabidae	2018	Day 0	0.03	0-1
			Day 14	0.03	0-1
			Day 28	0.03	0-1
			Day 56	0.09	0-2
	Carabidae	2019	Day 0	0	0
			Day 14	0	0
			Day 28	0	0
			Day 56	0	0
Winter	Dermaptera	2018	Day 0	0	0
			Day 14	0	0
			Day 28	0	0
			Day 56	0.13	0-2
	Dermaptera	2019	Day 0	0	0
			Day 14	0	0
			Day 28	0	0
			Day 56	0	0
Summer	Dermaptera	2018	Day 0	0	0
			Day 14	0.06	0-2
			Day 28	0	0
			Day 56	0	0
	Dermaptera	2019	Day 0	0.03	0
			Day 14	0	0
			Day 28	0	0
			Day 56	0	0

Winter	Formicidae	2018	Day 0	0	0
			Day 14	0.03	0-1
			Day 28	0	0
			Day 56	0	0
	Formicidae	2019	Day 0	0	0
			Day 14	0	0
			Day 28	1.16	0-14
			Day 56	0.03	0-1
Summer	Formicidae	2018	Day 0	0.63	0-8
			Day 14	0	0
			Day 28	0.09	0-1
			Day 56	0.03	0-1
	Formicidae	2019	Day 0	0.19	0-4
			Day 14	0.03	0-1
			Day 28	0.03	0-1
			Day 56	0.16	0-3
Winter	Collembola	2018	Day 0	0	0
			Day 14	0.06	0-1
			Day 28	0.81	0-11
			Day 56	0.72	0-5
	Collembola	2019	Day 0	0	0
			Day 14	0	0
			Day 28	0	0
			Day 56	0	0
Summer	Collembola	2018	Day 0	0.19	0-2
			Day 14	0.03	0-1
			Day 28	0.38	0-11
			Day 56	0	0
	Collembola	2019	Day 0	0	0
			Day 14	0	0
			Day 28	0	0
			Day 56	0	0
Winter	Staphylinidae	2018	Day 0	0	0
			Day 14	0	0
			Day 28	0.06	0-1
			Day 56	0	0
	Staphylinidae	2019	Day 0	0.19	0-1
			Day 14	0	0
			Day 28	0.97	0-9
			Day 56	0.34	0-4
Summer	Staphylinidae	2018	Day 0	0	0
			Day 14	0	0
			Day 28	0.06	0-1
			Day 56	0.44	0-13
	Staphylinidae	2019	Day 0	0.09	0-1
			Day 14	0.28	0-3
			Day 28	0	0
			Day 56	0.06	0-2

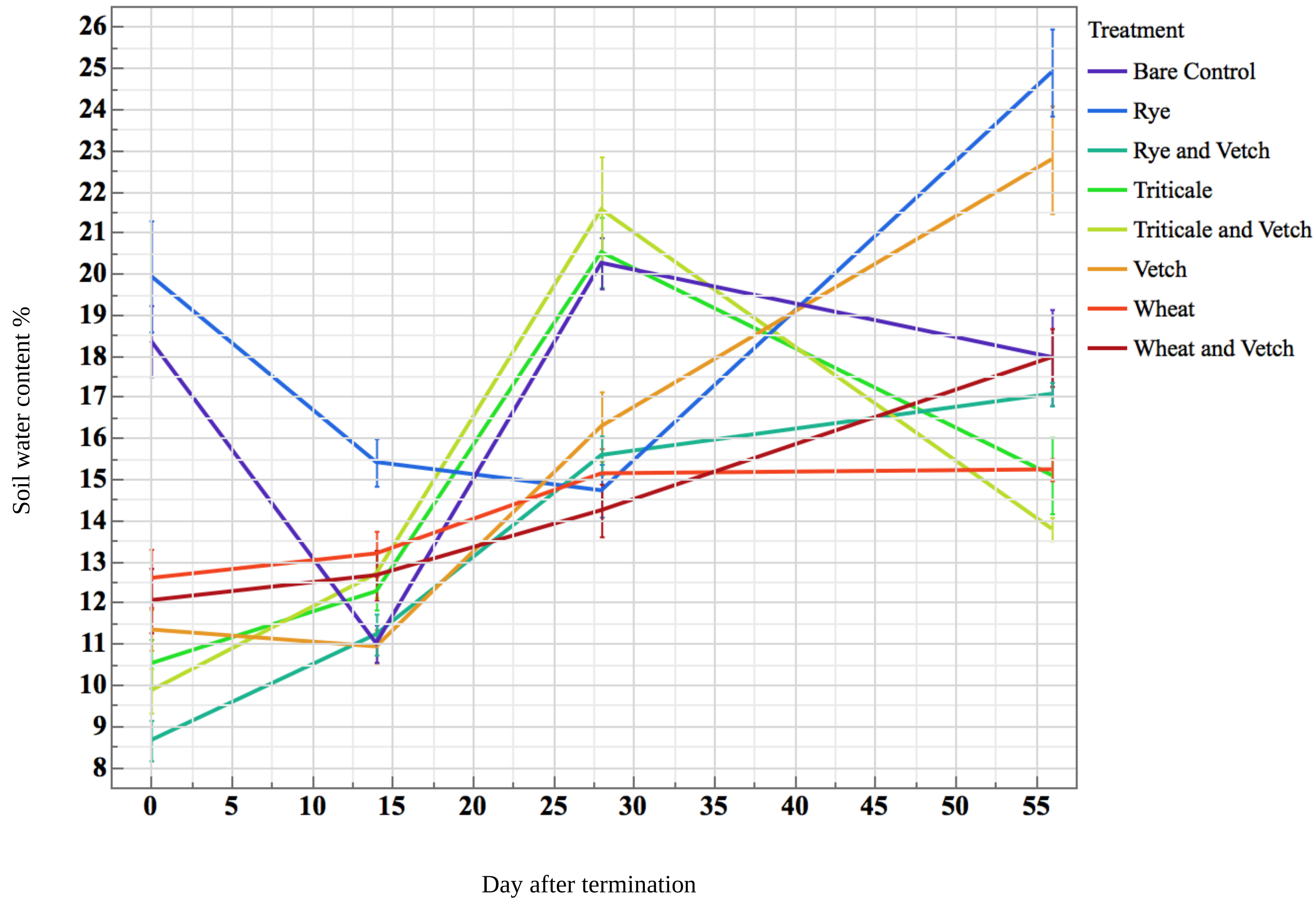

Figure 3-2: Mean percent soil water content for the 2018 and 2019 winter cover crop experiments. Soil moisture is based on gravimetric soil water content analysis. Vertical bars represent the standard error of the mean.

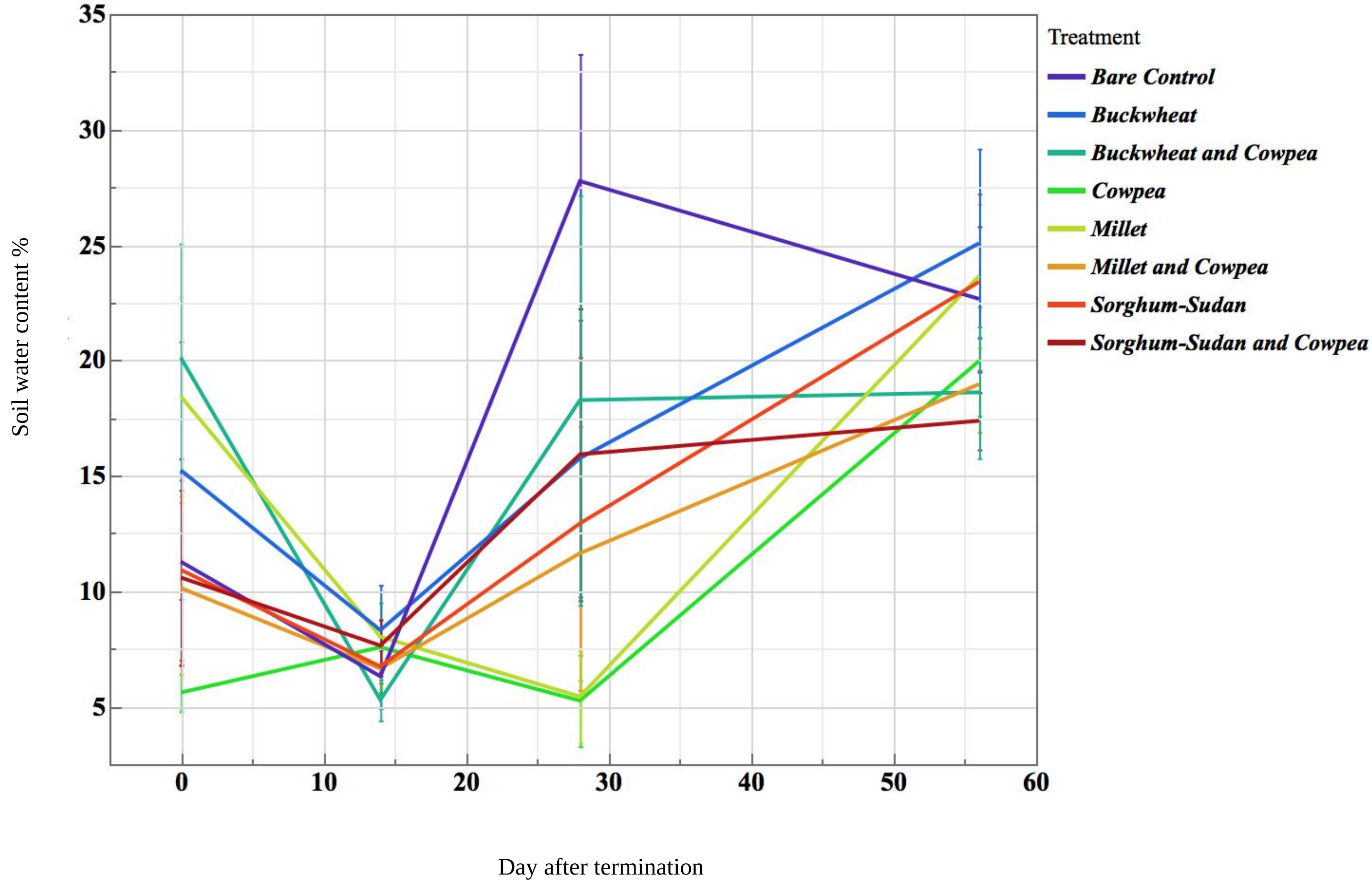

Figure 3-3: Mean percent soil moisture for the 2018 and 2019 summer cover crop experiments. Soil moisture is based on gravimetric soil water content analysis. Vertical bars represent the standard error of the mean.

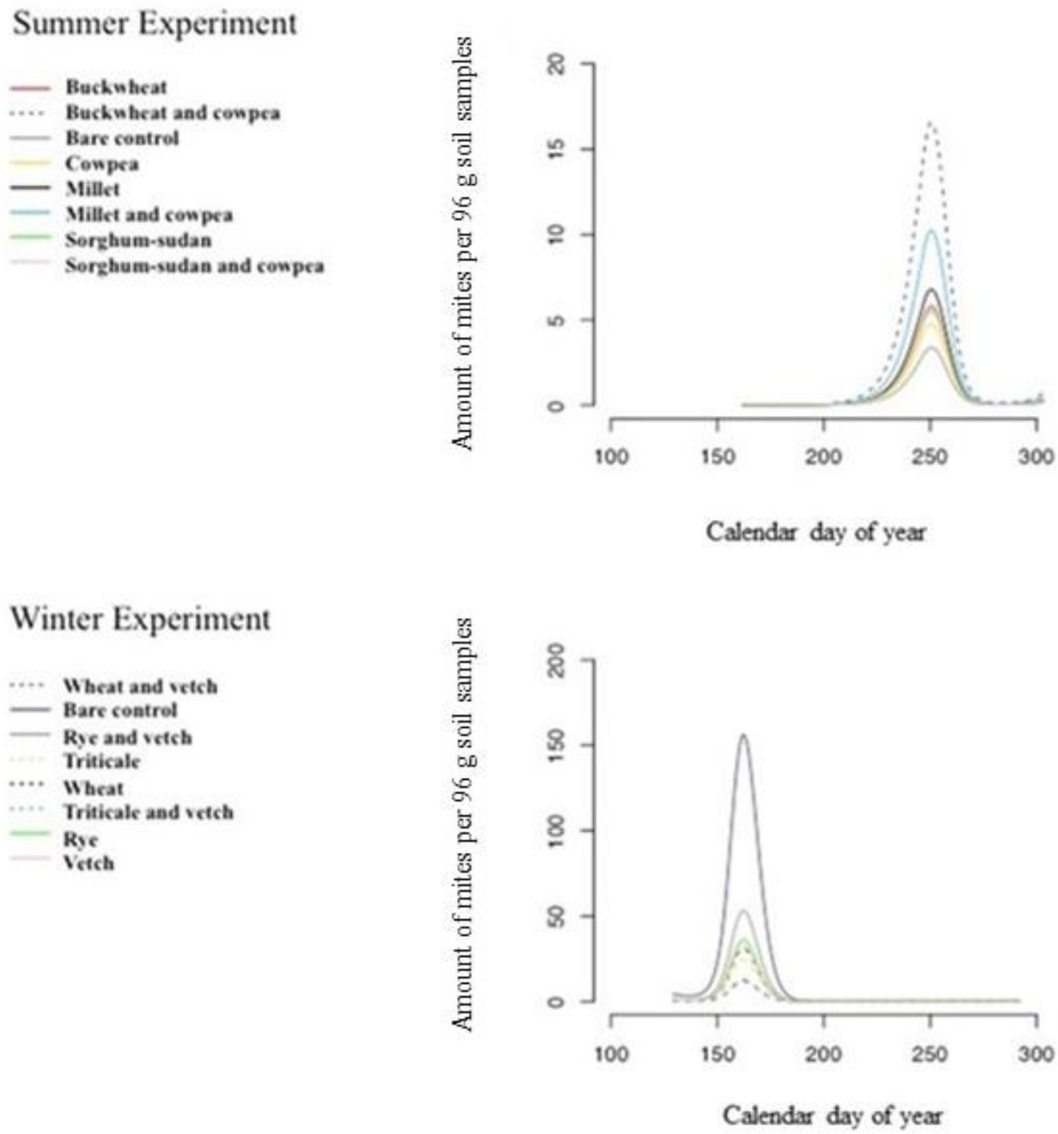

Figure 3-4: Expected mite abundance determined by the generalized additive statistical model. Abundance varies depending on cover crop type. Treatments that have a significant effect on mite abundance when compared to the bare control treatment are represented by dashed lines and the corresponding cover crop treatments are in the legend. The expected abundance depended on soil nitrogen, carbon, water content, and organic matter. Shown here is the expected mite abundance at the average soil nitrogen (2.5%), carbon (2.0%), water content (14.6%), and organic matter (4.1%) for the study. January 1 represents Day 1 of year and December 31st represents day 365.

https://trevorhefley.shinyapps.io/arachnid_plot/

Figure 3-5: Expected mite abundance determined by the generalized additive statistical model. Abundance varies depending on cover crop type with adjustable continuous predictor variables (water content/soil moisture, organic matter, total carbon, and total nitrogen).

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Appendix A

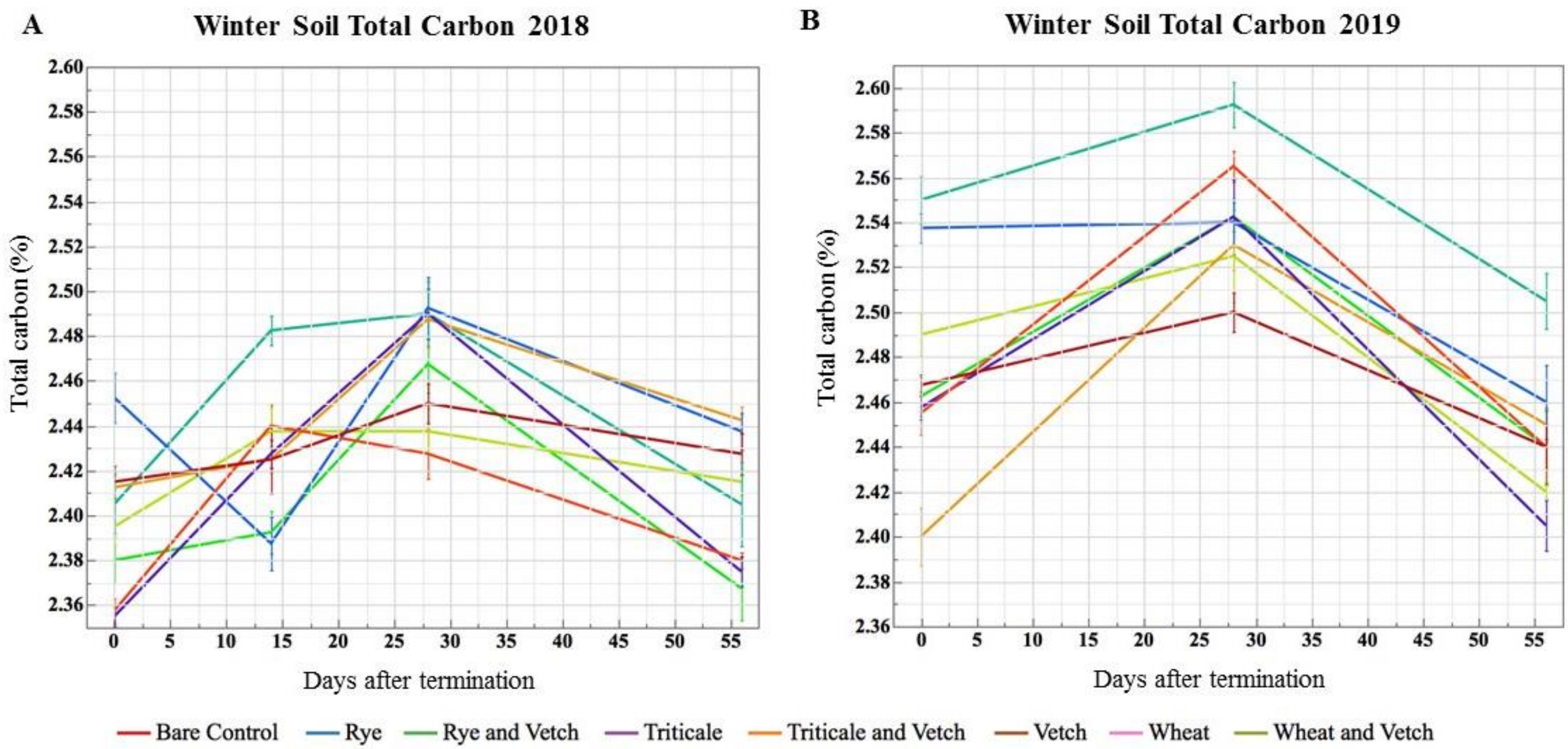

Figure A-1:Trend of fluctuations in total soil carbon days after winter cover crop termination (A) mean total soil carbon for year one of winter cover crops *(P<0.0001)*. Crops were planted in October 2017 and terminated (0 days after termination) on May 9, 2018 (B) mean total soil carbon for year two of overwintering cover crops *(P<0.0001)*. Crops planted in October 2018 and terminated (0 days after termination) on May 9, 2019. Each error bar is constructed using 1 standard error from the mean.

Appendix B

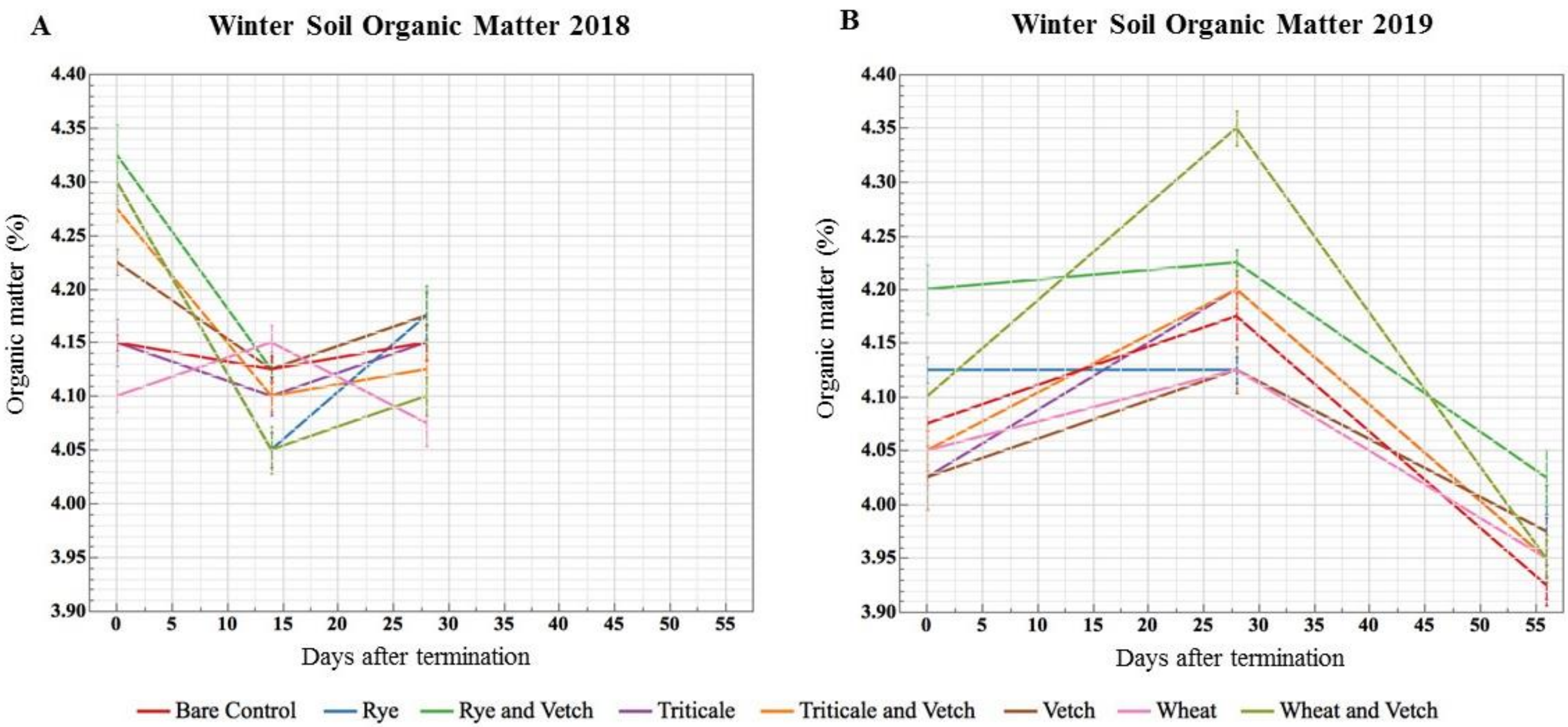

Figure A-2:Trend of fluctuations in soil organic matter days after winter cover crop termination (A) mean soil organic matter for year one of winter cover crops *($P<0.0001$)*. Crops were planted in October 2017 and terminated (0 days after termination) on May 9, 2018. Soil sampling for organic matter in year one only took place only on day 0, 14, and 28. (B) mean soil organic matter for year two of overwintering cover crops *($P<0.0001$)*. Crops planted in October 2018 and terminated (0 days after termination) on May 9, 2019. Each error bar is constructed using 1 standard error from the mean.

Appendix C

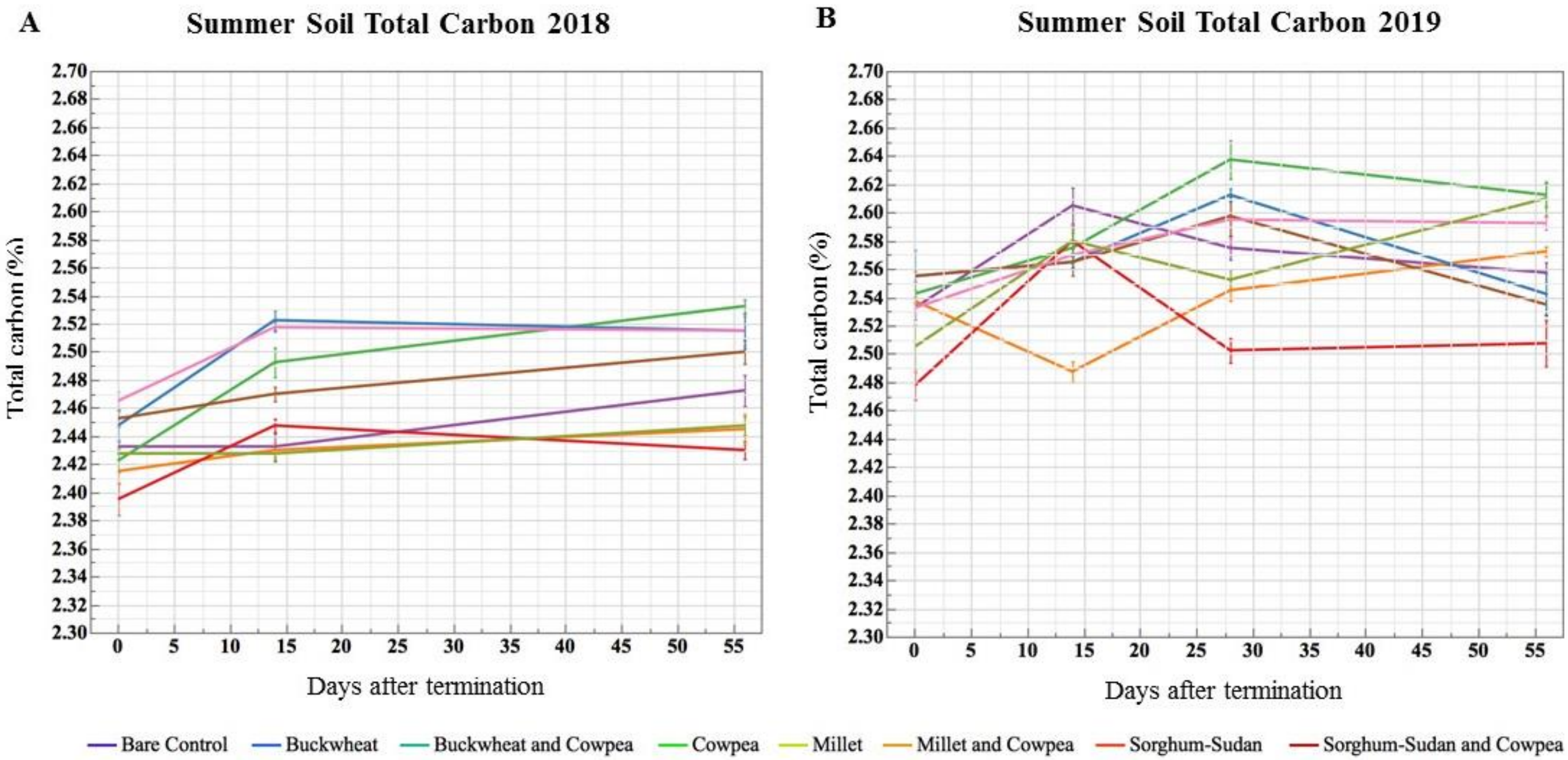

Figure A-3:Trend of fluctuations in total soil carbon days after summer cover crop termination (A) mean total soil carbon for year one of summer cover crops by treatment *(P<0.0001)*. Crops were planted in June 2018 and terminated (0 days after termination) on September 4, 2018 (B) mean total soil carbon for year two of summer cover crops by treatment *(P<0.0001)*. Crops planted in June 2018 and terminated (0 days after termination) on August 6, 2019. Each error bar is constructed using 1 standard error from the mean.

Appendix D

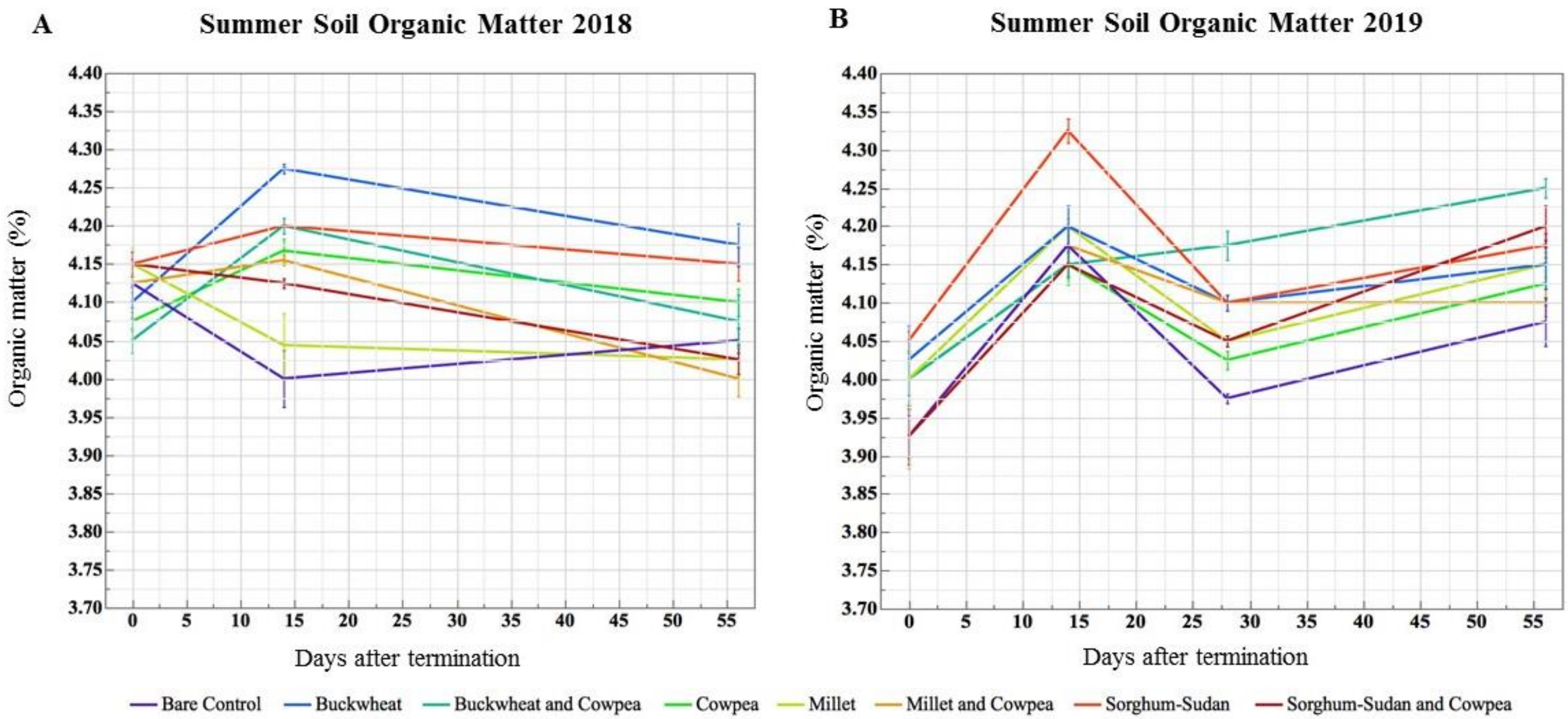

Figure A-4: Trend of fluctuations in total soil organic matter days after summer cover crop termination (A) mean total soil organic matter for year one of summer cover crops by treatment *(P<0.0001)*. Crops were planted in June 2018 and terminated (0 days after termination) on September 4, 2018 (B) mean total soil organic matter for year two of summer cover crops by treatment *(P<0.0001)*. Crops planted in June 2018 and terminated (0 days after termination) on August 6, 2019. Each error bar is constructed using 1 standard error from the mean.