INTERSEEDING COVER CROPS IN CORN: EVALUATING ESTABLISHMENT, COMPETITIVENESS, HERBICIDE OPTIONS, AND ECOSYSTEM SERVICES

By

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ABSTRACT

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Farmers could enhance crop diversity in their farming systems by interseeding cover crops in corn in late May and June in corn rotations in the Upper Midwest. Recommendations must be developed for cover crop species, seeding rates, and interseeding timings that optimize cover crop growth and enhance corn production. Weeds must be controlled, and cover crops must establish in this system. Cover crops influence soil health in long term studies; however, the influence of interseeded cover crops on soil enzymes, soil structure, and nutrient cycling has not been reported. In Michigan, two experiments were conducted from 2015-2017 and one experiment from 2017-2019. In the first experiment, annual ryegrass, crimson clover, oilseed radish and a mixture of the three species were broadcast interseeded at each of the V1 through V7 corn stages at a single seeding rate. Cover crop and weed density and biomass were measured during the growing season, at the time of corn harvest, and the following spring. Soil samples were taken in the spring in the year following interseeding and analyzed for inorganic N, extracellular enzyme activity, and aggregate stability. Corn was planted as an indicator crop and sampled for C and N content. In the second experiment, preemergence (PRE) and postemergence (POST) herbicides were applied, and cover crops interseeded at the V3 and V6 corn stages. Cover crops were evaluated in October for injury and stand loss. A greenhouse trial was also included to evaluate cover crop response to herbicides. In the third experiment, the same three cover crop species and a mixture of annual ryegrass and crimson clover were interseeded at three seeding rates in V3 and V6 corn. Establishment, biomass, and corn grain yield were collected

using the same methods as previously described. Eight on-farm locations were interseeded with the same cover crop species at the 1X rate at the V3 and V6 corn stages. All plots were flown with a fixed-wing aircraft to measure canopy temperature. Small-plots were flown with UAV to acquire multispectral imagery to determine NDVI and NDRE. In years with normal or below normal precipitation, annual ryegrass and oilseed radish produced the highest biomass. Establishment improved when seeding on tilled soil compared with no-till soil. All cover crop species established, regardless of tillage, with above normal rainfall. Both annual ryegrass and crimson clover established when interseeded as a mixture at the seeding rates used. Increasing seeding rates usually increased biomass production. Cover crops could be interseeded at any time from V1-V7 corn if weeds were controlled. No cover crop species was competitive with summer annual weeds; annual ryegrass was the only species that overwintered and suppressed winter annual weeds. There were PRE and POST options for weed control with all cover crop species, but farmers must be mindful of herbicide and cover crop combinations. Delaying interseeding until V6 may reduce injury from some PRE herbicides. In the year of interseeding, cover crops did not reduce corn grain yield; therefore, remote imagery was not able to detect changes in corn health. Remote imagery detected cover crop establishment in the V3 interseedings prior to corn canopy closure; remote imagery did not detect less thermal stress where cover crops were interseeded. Annual ryegrass plots had reduced spring inorganic N content, and this sometimes translated to reduced N in the indicator corn crop. Success of broadcast interseeded cover crops is highly depended on adequate precipitation; this practice would be especially successful where summer rainfall is consistent or in irrigated systems. Benefits of cover crops are likely to be realized over multiple years of interseeding; farmers must balance goals of cover cropping with costs of seeding when selecting species, seeding rates, and weed control options.

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CHAPTER 1

LITERATURE REVIEW

Cover Crop Use Overview

According the USDA's 2012 Census of Agriculture, cover crops are planted on less than 2% of row cropping hectares, with nearly half of those hectares in Midwestern states (USDA, 2014). A survey of cover cropping practices in the U.S. was conducted by the Sustainable Agriculture Research and Education Program and the Conservation Technology Information Center. The major reasons that farmers' plant cover crops include improving soil health, soil organic matter (SOM), and fertility, reducing soil erosion, controlling weeds, reducing disease and insect pressure, gaining N credits from some cover crops, and increasing cash crop yield. Due to the current low commodity prices, many producers are less likely to plant cover crops, despite the knowledge of the benefits they provide. Furthermore, many producers are often unsure of what cover crops to plant in their rotations, are unwilling to assume the added financial risk associated with planting cover crops, have problems with cover crop establishment, do not have the time or labor to manage cover crops, and do not see an economic return from cover crops (SARE, 2016). These factors indicate a need to improve farmer knowledge of the benefits of cover crops and how to manage cover crops in producers' rotations.

In Michigan, cover crops were planted on about 177,000 ha in 2012, which is about 6% of the total cropland in the state (USDA, 2014). A survey of cover crops in the state was conducted in 2016 by the Michigan Agriculture Environmental Assurance Program. The survey found that most farms do not plant cover crops for various reasons including additional production costs from planting, worries about compatibility with herbicides, or lack of time for planting following cash crop harvest. Producers that do plant cover crops believed cover crops improve soil health, nutrient cycling, and the profitability of their farms over the long term (MAEAP, 2016).

Cover Crop Interseeding Overview

Interseeding cover crops is not a new concept. For example, a USDA publication from 1913 recommends interseeding crimson clover into corn following the final interrow cultivation. After many years of this practice, corn yields were reported to increase from 0.63 Mg/ha to up to 4.4 Mg/ha (Westgate, 1913). More recently, a red clover cover crop is often frost seeded in winter wheat in March and April in Michigan; alternatively cover crops are planted in early August after wheat harvest. Cereal rye is planted after soybean or corn harvest in the fall. Aerial seeding either cereal rye or annual ryegrass into corn in August or September is another window for seeding grass cover crops. In Michigan and the northern Corn Belt, corn harvest often occurs in October and November, which severely limits cover crop seeding following harvest. To provide farmers with more cover cropping options in a corn rotation, one solution is to interseed cover crops into corn at the early vegetative stages, such as V1 through V7. Unlike aerial seeding late in the season, interseeding cover crops early in the season may pose a risk to corn productivity. For example, two concepts in weed control are the critical period for weed control and the critical weed-free period. The critical period for weed control is the time when weeds must be controlled before corn yield loss will occur. The critical weed-free period is the length of time corn must remain weed-free before yield loss will occur (Hall et al., 1992). In corn, the critical weed free period has been determined for different growing regions and different weeds. In Ontario, the critical weed free period was determined to be 6 leaf tips before weeds could emerge without causing yield loss (Hall et al., 1992). When itchgrass emerged at V2 or later, there was no yield loss (Strahan, 2000), when barnyardgrass emerged at V4 or later there was no yield loss (Travlos, 2011), and when giant ragweed emerged at V5 or later no yield loss was reported (Harrison, 2001). These results show that summer annual weeds are highly competitive with corn depending on the time of emergence and control.

There are key differences that should be considered when comparing the competitiveness of cover crops to weeds in corn. Cover crop species such as annual ryegrass, cereal rye, crimson clover, red clover, oilseed radish, and winter rape are winter annual species that prefer cooler conditions. Summer annual weeds may grow more aggressively than cover crop species. Secondly, cover crops do not emerge immediately when seeded. Depending on soil moisture conditions, cover crops may experience a 5-day lag time from seeding to emergence, especially with broadcast interseedings (Renner et al., 2016). Rainfall after interseeding is one of the most important factors for success in broadcasting interseeding cover crops (Constantin et al., 2015; Tribouillois et al., 2018; Wilson et al., 2014; Collins and Fowler, 1992). Since this lag time exists, cover crops will not immediately compete with the corn crop, and this risk is reduced as interseeding timing is delayed, at V7 instead of V3, for example. Finally, cover crop species may differ in their competitiveness with corn, so cover crop species selection, as well as seeding rate, could be important factors for avoiding yield loss to corn.

Grass Cover Crops

Annual Ryegrass

Plant Characteristics

Annual ryegrass used in cover cropping in the United States is usually Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.)). Italian ryegrass can hybridize freely with perennial ryegrass (*Lolium perenne*), rigid ryegrass (*Lolium rigidum*), darnel or poison darnel (*Lolium temulentum*), and remote ryegrass (*Lolium remotumi*) which can make this species difficult to identify and cause the spread of herbicide resistance and invasive characteristics (CABI, 2018). According to the USDA Plant Fact Sheet, annual ryegrass is an annual or biennial plant and grows from about 61 cm to 91 cm tall. Each plant grows in a bunch form with many tillers with long, narrow leaves extending from the base of the plant. Leaves are glossy on the underside which can help with identification. It is commonly used as a fast-growing cover crop (USDA annual ryegrass, 2002) to help fight erosion, improve soil health, suppress weeds, and scavenge nutrients (Clark, 2007). Annual ryegrass is also used as a high-yielding species for pastures (CABI, 2018).

For management purposes, the Midwest Cover Crop Council recommends seeding annual ryegrass between 23 and 35 kg/ha for broadcast seedings and 12 to 23 kg/ha for drilled seedings (Clark, 2007). Given proper growing conditions, germination and time to emergence is rapid for this species. Gramshaw et al. (1976) studied annual ryegrass germination under different temperature and light regimes. Germination was fastest at 23°C at just under two days to 50% germination; as temperatures increased to 35°C and decreased to 8°C, time to 50% germination decreased to greater than two days and six days, respectively. The highest germination percentage occurred at 27°C. Therefore, under summer conditions in Michigan, which average about 14°C minimum and 27°C maximum temperatures for June and July, annual ryegrass should germinate quickly if there is soil moisture and have a high rate and percentage of establishment.

Annual ryegrass produces a wide range of biomass depending on the climate and the seeding date, and 30-45% of the biomass is contained in the roots (Meisinger et al., 1991). According to Clark (2007), it can produce between 2300 and 10,400 kg ha^{-1} as an individual species seeding. In terms of relative growth rate (RGR), little research has been conducted. Hunt (1975) determined the maximum RGR for many species under optimal conditions. Perennial ryegrass, closely related to annual ryegrass, had a maximum RGR of 0.13 g/g/day. The authors note that RGRs in field conditions would be much lower. Another study found that the RGR of perennial ryegrass was 0.214 g/g/day grown in controlled conditions rather than in the field (Poorter and Remkes, 1990).

Another important consideration for interseeding annual ryegrass into corn is shade tolerance. In Missouri silvopasture research, annual ryegrass biomass was reduced by 21 and 36% in separate years in shaded compared with no shade treatments (Kallenbach et al., 2006). In another silvopasture experiment in Mississippi there was no difference in annual ryegrass emergence in response to shade; however, biomass was reduced by 50% under 50% shade and 72% under 75% shade. Plant height was also reduced by nearly half in the 50% shade treatment and by more than 50% under the 75% shade treatment (Watson et al., 1984). Finally, red:far-red light is often used to test shade response of plants. Red light reaches plants when there is no shade while far-red light passes through plant canopies and indicates a shaded environment. Under lower red:far-red light, annual ryegrass tillering was found to decrease, while tillering increased with increasing red:far-red (Casal et al., 1987; Deregibus et al., 1983).

Use in Interseeding Research

Annual ryegrass has been used in corn interseeding research on many occasions both as a single species and in mixtures (Abdin et al., 1998; Abdin et al., 1997; Curran et al., 2018; Grabber et al., 2014; Scott et al., 1987; Zhou et al., 2000). A study from Canada tested the effects of broadcast-interseeded annual ryegrass on corn yield. Corn was planted in mid-May at 80,000 seeds/ha with 76-cm row spacing. Annual ryegrass was seeded at 8 kg ha^{-1} in a mixture with red and white clovers. Corn grain yield was not reduced; however, the authors did not note information about the cover crop.

Curran et al. (2018) compared the establishment and biomass production of drill-interseeded cover crops in the mid-Atlantic region and determined the effects of interseeded cover crops on corn grain yield. Corn planting dates ranged from early to late May depending on the site year. Corn was planted in 76-cm rows between 69,000 to 87,000 seeds/ha. Annual ryegrass was seeded from V2 to V6 corn at 22.4 kg/ha as a single species and at 11.2 kg/ha in a mixture with red clover, crimson clover, and hairy vetch. Fall biomass of annual ryegrass ranged from 8 kg/ha to 1560 kg/ha with an average of 250 kg/ha. Spring biomass ranged from 16 kg/ha to 2830 kg/ha with an average of 250 kg/ha. Biomass was limited where N was likely limited based on fertility and management history of the field. Corn yields were reduced when cover crops were seeded at V2 and the authors noted a potential for yield loss at V3 compared with later corn growth stages; however, weed pressure was not noted in the paper. Finally, corn seeding rates of 75,000 seeds/ha and less were determined to be rates that would not be too competitive for cover crops. Seeding rates above 75,000 seeds/ha created a competitive system not suitable for seeding cover crops (Curran et al., 2018).

Grabber et al. (2014) analyzed the upper Midwestern region of the United States for cover crop interseeding and found that interseeded annual ryegrass usually provided greater groundcover and soil-nitrate scavenging potential than a fall-seeded cereal rye crop. The authors also conducted a 4-year experiment with annual ryegrass interseeded on June 11th at 34 kg/ha, following corn planting on May 9th at 82,000 seeds/ha in 72-cm rows. In continuous corn, maximum corn grain yields were achieved where annual ryegrass was planted with a manure application. Scott et al., (1987) conducted an interseeding experiment in New York. Corn was planted from early May to early June each year at two different seeding rates of 64,000 and 74,000 seeds/ha in 76-cm rows. Annual ryegrass was interseeded at 0.15-m tall corn and 0.3-m tall corn. Annual ryegrass produced an average of 2541 kg/ha and 29 kg N/ha was stored in its biomass. Corn yield was unaffected by annual ryegrass interseedings.

Zhou et al., (2000) conducted an interseeding experiment with irrigated corn and annual ryegrass in Quebec, Canada. Corn was planted in late May in 76-cm rows at 63,000 to 71,000 seeds/ha. Annual ryegrass was drill-interseeded at 28 kg/ha 10 days after planting which was prior to corn emergence. Weeds were not controlled in the first year, but bentazon was applied for broadleaf weed control in the second year of the experiment. Corn grain yield was unaffected by the presence of ryegrass. In the wet year of the experiment, 1800 kg/ha of annual ryegrass biomass was produced while only 400 kg/ha of biomass was produced in the dry year.

Research to determine the effects of corn planting density on cover crops and grain yield was conducted in New York, Pennsylvania, and Maryland (Youngerman et al., 2018). Corn was planted in May at each location at three different densities: 37,050, 74,100, and 111,150 plants ha^{-1}. A mixture containing 51% cereal rye, 25% annual ryegrass, 14% hairy vetch, and 10% red clover by weight was interseeded at the V5 corn stage. Weeds were controlled using interrow cultivation prior to interseeding cover crops. Corn grain yield was lower at the 37,050 plants ha^{-1} seeding rate at one location. Cover crop biomass was reduced as corn seeding rate increased, but cover crops did not affect corn grain yield.

Effects on N cycling

Annual ryegrass is rated as an excellent N scavenging species in Managing Cover Crops Profitably (Clark, 2007). When studied as a weed, annual ryegrass took up more NO_3 compared with wheat (Liebl and Worsham, 1987), and another experiment found that annual ryegrass was more than twice as efficient as wheat in converting N to grain (Hashem et al., 2000). Curran et al. (2018) explain that annual ryegrass biomass was reduced on sites that had lower N in the soil and stated that annual ryegrass is a good cover crop for high-fertility areas to help protect the soil from N loss. An experiment from Wisconsin found that fall soil residual NO_3 was 2.77 mg/kg while rye was 5.68 mg/kg and the no cover treatment had 4.67 kg/ha (Grabber et al., 2014). Zhou et al. (2000) found that uptake of soil N was higher in the annual ryegrass plots compared with corn-only treatments, but this additional uptake was a result of greater uptake of mineralized soil N rather than N applied as fertilizer. Finally, Kramberger et al. (2009) found that mineralizable N was reduced in annual ryegrass plots in the fall, but annual ryegrass had a much higher C:N compared with crimson clover and subterranean clover, which affects the N availability for the following crop.

Cereal Rye

Plant Characteristics

Cereal rye (*Secale cereale*) is another commonly used grass cover crop in the United States. It is an annual, cool-season grass that has an erect growth habit. It can grow between three and six feet tall prior to flowering (USDA Cereal Rye, 2002). According to Clark (2007), cereal rye is most commonly used as a cover crop because it scavenges N, reduces erosion, fits many rotations, produces high amounts of biomass, suppresses weeds and other pests, and can be used as a companion crop. Other than its use as a winter cover crop, it is used as a spring forage, pasture, or in haylage (USDA Cereal Rye, 2002).

As a winter annual cover crop, cereal rye is commonly seeded at 70 to 140 kg/ha in drilled seedings. In broadcast seedings in the fall, it is optional to increase seeding rates to as high as 400 kg/ha. Seeded as a mixture with clovers, about 70 kg/ha is recommended (Clark, 2007). Optimal temperatures for germination vary; one study compared cereal rye emergence at 5°C, 10°C, 15°C, 20°C, 25°C and 30°C. Rye emergence was reduced to 88% at 30°C, which was still quite high; however, under this high temperature and low water potential, -1.5 MPa, germination was further reduced to 83%. Time to 50% emergence increased with increasing temperature and cereal rye had a faster emergence rate compared with wheat, downy brome, and canola (Blackshaw, 1991). Kallenbach et al. (2006) found that spring temperatures of -4°C and -11°C limited the spring growth of both cereal rye and annual ryegrass. Another experiment found that temperatures above 42°C for over one week caused cereal rye senescence. Cereal rye was also susceptible to freezing death at temperatures below -25°C (Fu et al., 1998).

Cereal rye produces large amounts of biomass when seeded as a winter annual. Clark (2007) stated that rye can produce anywhere from 2300 to 11,500 kg/ha of biomass. Snapp et al.

(2005) found that fall-seeded cereal rye in Michigan produced 800-2,900 kg/ha. Cereal rye seeded in September following wheat produced between 7900-12,800 kg/ha of dry biomass prior to spring termination (Hill et al., 2016). In the Northeastern region, average rye biomass was 9700 kg/ha when harvested at flowering (Mirsky et al., 2017). Mirsky et al. (2011) reported maximum biomass of cereal rye to be 12,000 kg/ha when seeded in August and harvested in May, with average biomass ranging from 4000-8000 kg/ha. Increasing the N supply to cereal rye also increased biomass in this experiment (Mirsky et al., 2011). The RGR of cereal rye was measured in an experiment in Australia and determined to be 0.04 g/g/day (Muldoon, 1986). White et al. (1991) measured the RGR of cereal rye grown at different temperatures. At constant 20°C temperatures, the RGR was 0.16 g/g/day; at constant 8°C temperatures, RGR was 0.118 g/g/day; at 20°C daytime and 8°C nighttime temperatures, RGR was 0.064 g/g/day.

For use in interseeding, it is important to consider shade and light responses of cereal rye. Cereal rye was suggested as a good crop to use for interseeding because of shade tolerance in a survey of farmers in Michigan (Snapp et al., 2005); however, the USDA-NRCS lists cereal rye as a shade-intolerant species (USDA Cereal Rye, 2002). Few studies have examined shade response of cereal rye as it is usually used as a weed suppressor rather than an interseeded cover crop subjected to shade. Kallenbach et al. (2006) found that shade caused a biomass reduction of up to 36% when cereal rye and annual ryegrass were grown in a silvopasture mixture. An experiment using cereal rye grown in Canada found that carbon assimilation was reduced in plants grown at cooler temperatures compared with warmer temperatures. This indicates that cereal rye was more effective at using light at higher temperatures compared with cooler temperatures (Hurry et al., 1995). Based on limited research and conflicting sources on shade tolerance, it is unclear if cereal rye would be a good crop for interseeding based on shade tolerance.

Use in Interseeding

An early experiment in Nebraska irrigated fields used cereal rye for interseeding following the final field cultivation (Olson et al., 1986). The average corn planting date was May 6th over 15 years, and the row spacing was 76-cm with 62,000 seeds/ha. After 10 years of interseeding continuous corn with cereal rye, corn grain yields were 0.59 Mg/ha higher than plots with no cover crop. The authors explain this may have been due to improved weed suppression from the cereal rye or improved soil structure (Olson et al., 1986). One experiment from Canada seeded cereal rye at 110 kg/ha, 10 and 20 days after corn emergence. Corn planting date, seeding rate and row spacing are listed previously in Abdin et al. (1998). There was no grain yield reduction from interseeding cereal rye, but biomass, RGR, and other data specific to the cereal rye were not reported. Cereal rye was also interseeded into seed and sweet corn in Canada (Belfry and Van Eerd, 2016). Corn was planted in 76-cm rows in mid-May to early June at 55,000 seeds/ha and 84,000 seeds/ha for sweet and seed corn, respectively. The cereal rye seeding rate was 101 kg/ha. Seed and sweet corn yields were unaffected by cover crops. Cereal rye produced 725 kg/ha of biomass which was lower than oilseed radish, but higher than crimson and red clovers (Belfry and Van Eerd, 2016). Noland et al. (2018) evaluated drilled, broadcast + incorporation, and broadcast seeding methods for interseeding cereal rye (168 kg/ha) at V7 corn. Fall biomass was 60 kg/ha for drilled seedings and between 20-30 kg/ha for the other seeding methods. Spring biomass, though, was not different for seeding methods and was about 1000 kg/ha (Noland et al., 2018). Cereal rye is rated as very good for interseeding into corn by Managing Cover Crops Profitably (Clark, 2007).

Effects on N Cycling

As previously stated, cereal rye is known for its role in cover cropping as an N scavenger. In a study that evaluated the ability of cereal rye to uptake applied fertilizer N, cereal rye was able to uptake about 50% of the applied N on average (Mirsky et al., 2017). In another experiment, cereal rye was planted in the fall following corn and soybean and harvested following termination in the spring. Soil inorganic N was lowest in the plots with cereal rye (Chu et al., 2017). Additionally, cereal rye plots sampled in the spring following seeding contained 44 and 31 kg N/ha for interseeding timings of mid-silk and postharvest, respectively (Scott et al., 1987). Adeli et al. (2011) found that cereal rye N uptake increased as poultry litter increased, which indicated that under high N, the concentration of N in the plant also increased. Wilson et al. (2013) found that at least 300 kg/ha of cereal rye biomass was required to uptake 10 kg/ha of N. One study did find that residual soil NO_3 was not reduced when cereal rye field plots were sampled in the fall compared with the no cover control treatment. For the following crop, cereal rye reduced soil N in soybean plots, but soybeans in those plots had higher N content for about six weeks after planting. After this time, the authors believed that nodulation took over for N acquisition (Wells et al., 2013).

Brassica Cover Crops

Oilseed Radish

Plant Characteristics

Oilseed radish (*Raphanus sativus* L.) has many common names such as forage radish, fodder radish, Tillage Radish®, radish ripper, daikon radish, and Japanese radish. Sometimes, distinctions are made between oilseed and forage radishes, with oilseed radishes having a wider, branched root; the reality is that radish varieties can hybridize, and distinctions are often too difficult to make between varieties (Jacobs 2012). Oilseed radish is in the Brassicaceae family of plants and is a winter annual. The leaves are arranged in a basal rosette and can grow up to 61 to 91 cm tall. The plant also develops a taproot that can grow 2.5 to 5 cm in diameter and up to 30 cm deep in the ground, which is one of the major factors that differentiates it from edible radishes (Jacobs, 2012). Oilseed radish is an effective nutrient scavenger because of its fast growth and large biomass. It is also used to relieve soil compaction and suppress weeds. Oilseed radish is a close relative of the cultivated food radishes such as cabbage, kale, and turnip (Clark, 2007).

Oilseed radish can be seeded at various times during the growing season, but oilseed radish plants cannot survive freezing temperatures, especially below 20°C (Sundermeier, 2008). An experiment was conducted using fluctuating versus consistent temperatures to determine optimum temperatures for oilseed radish germination. The highest germination was achieved by 17.5/2.5°C fluctuating temperatures, and 5°C single temperature (Malik et al., 2010).

Oilseed radish seeding rates are variable based on the use of the crop. Lower seeding rates of 6 kg/ha will produce larger taproots that can break up compaction; higher seeding rates of 17-23 kg/ha will produce smaller tap roots that may be useful for the uptake of more nutrients, for better efficiency as a trap crop for nematodes, or for better pest and weed suppression (Jacobs, 2012). The recommended seeding rate from Managing Cover Crops Profitably is 12-23 kg/ha for a broadcast seeding and 9-15 kg/ha for drilled seedings (Clark, 2007).

Various experiments have been conducted using oilseed radish as a cover crop. Gfeller et al. (2018) seeded oilseed radish at 30 kg/ha following a cereal grain crop and aboveground biomass was 1580 kg/ha. Vyn et al. (2000) seeded oilseed radish at 20 kg/ha following wheat and aboveground biomass was 1400 kg/ha. Lawley et al. (2012) seeded oilseed radish at 14 kg/ha and biomass was 7250 kg/ha; however, irrigation was used to stimulate germination in this experiment. Wang et al. (2008) found that radish seeded at 20 kg/ha in August produced 6262 kg/ha of biomass by October in Michigan. In a Minnesota experiment, fall-seeded radish at 19 kg/ha produced 4400 kg/ha of biomass with root biomass comprising more than half of the biomass (Gieske et al., 2016). From these results, it is apparent that biomass production by oilseed radish is affected by factors outside of seeding rate. For RGR, one experiment used growth chamber experiments to test the effects of elevated CO_2 levels on oilseed radish RGR. The results showed that under ambient (350 µmol/mol) CO_2 the relative growth rate was 0.229 g/g/day and increased to 0.264 g/g/day under elevated CO_2 (750 µmol/mol). These were maximum RGRs at 20 days after planting. RGR dropped to about 0.75 g/g/day by 45 days after planting (Usuada and Shimogawara, 1998).

The effects of light and shade have been studied for oilseed radish; however, most of the studies are on wild radish or cultivated, edible forms of oilseed radish. In an experiment using wild radish, germination was inhibited by far-red light, or shaded light (Malik et al., 2010). This indicates that shade could impact radish species in an interseeded scenario. Another experiment evaluated the growth of oilseed radish under different light levels in growth chambers. These light levels were equal to 2.2%, 4.3%, 6.5%, and 11% of full sunlight. Plants started from the same size before they were placed under the shaded treatments. Plants growing under 11 and 2.2% light gained 600 and 480 mg of biomass in the 14-day trial period, respectively (Nieman and Poulsen, 1971). While these differences were significant, oilseed radish was able to grow under heavily shaded conditions. Finally, oilseed radish leaf area increased by 50% with an 80% reduction in light compared with the full light treatment in a growth chamber experiment (Poorter and Evans, 1998). This indicates that leaf area increases with increasing shade to capture more light.

Use in Interseeding

Oilseed radish has not been used as frequently as grass and clover species for early interseeding of cover crops in corn. Researchers at Pennsylvania State University have successfully interseeded oilseed radish into corn at the V5-V7 growth stages (Roth et al., 2015). Also, oilseed radish was interseeded into sweet and seed corn in Canada (Belfry and Van Eerd, 2016). Oilseed radish seeded at 17 kg/ha at V6-V8 corn produced the highest fall biomass of 1767 kg/ha compared with cereal rye, crimson clover, and red clover. Oilseed radish did not reduce corn grain yield.

Effects on N Cycling

As stated previously, oilseed radish can be an effective N scavenger (Clark, 2007); however, it is important to note that in northern climates, oilseed radish winterkills and the N release is not always synchronous with the following cash crop (Clark, 2007). Belfry and Van Eerd (2016) found that oilseed radish aboveground biomass combined across interseeding timings of V4-V6 and V8-V10 contained 70 kg/ha of N in the fall, which was higher than aboveground biomass N of cereal rye (24 kg/ha), crimson clover (15.5 kg/ha), and red clover (13.5 kg/ha). Oilseed radish seeded in August at 20 kg/ha in Ontario had an N content of 19 kg/ha in aboveground biomass when harvested in October, which was lower than cereal rye and red clover (Vyn et al., 2000). Hill et al. (2016) seeded oilseed radish in August following wheat prior to dry bean planting the following spring; soil inorganic N measured biweekly after dry bean planting was occasionally reduced in this experiment, but this never affected dry bean growth or yield. Radish increased N_2O soil release by 39% and 323% compared with cereal rye and the no cover treatment, respectively. Measurements were taken weekly following cover crop planting (Thomas et al., 2017). While this is likely N that is not leaching, it is also increasing the release of a powerful greenhouse gas.

Brassica napus

Many brassica plants are in the family of rapeseed with the scientific name *Brassica napus*. According to Clark (2007), brassica cover crops are known for rapid and large fall growth as well as their ability to scavenge nutrients. Some are also known for their ability to break up compaction and serve as a trap crop for harmful crop pests. Members of *B. napus* are annuals or are spring planted and are used for industrial oils and forages beyond their use as cover crops. While many cultivars winterkill, some are able to withstand temperatures as low as -12°C (Clark, 2007). *B. napus* grows from a single crown and can grow between 3 and 4 feet tall (USDA Plants, 2018).

One experiment found that *B. napus* that overwintered produced similar biomass to winter wheat at 1816 kg/ha. Rathke et al. (2006) found that *B. napus* often produced about 1600 kg/ha of spring biomass when N was available and about 800-1200 kg/ha when N was more limiting. Cumbus and Nye (1982) determined the RGR of *B. napus* at different root zone temperatures. The RGR was determined to be 0.24 g/g/day, 0.35 g/g/day, 0.39 g/g/day, 0.40 g/g/day, and 0.34 g/g/day at 10°C, 15°C, 25°C, 30°C, and 35°C, respectively. This indicates optimal soil temperatures of 25°C and 30°C with 15C and 35°C being acceptable as well. The soil temp of 10°C was too cold for optimal RGR. Diepenbrock (2000) showed that the growth rate of *B. napus* increased as light interception increased and decreased by 67% when light interception dropped from 80% to 40%. Finally, *B. napus* is known for its ability to uptake N; however, much of the N is immobilized in the leaves and reenters the environment upon termination. For *B. napus* seed production, only 48% of the N taken up was recovered in the seed. This indicates the high potential for this species to release N back into the environment, potentially at times not valuable for crop production (Rossato et al., 2001). *B. napus* has not been used in recent corn interseeding experiments.

Clover Cover Crops

Crimson Clover

Plant Characteristics

Crimson clover (*Trifolium incarnatum* L.) is a commonly planted clover species in the United States (Young-Mathews, 2013). It is an annual legume that forms a densely hairy rosette with unbranched stems growing one to three feet tall. Leaves are trifoliate with leaflets that are heart-shaped with rounded edges and lacking a watermark. Crimson clover is commonly used as a cover crop (single species or in mixtures), as a green manure for N, as a forage for both livestock and wildlife, as a weed suppressor, and as a beneficial insect host (Young-Mathews, 2013). Crimson clover is an important cover crop because it provides nitrogen to the cropping system and can provide nutrient cycling benefits (Clark, 2007).

As a winter annual cover crop, crimson clover must be seeded six to eight weeks prior to the first frost to allow for establishment prior to freezing temperatures; too early of seeding will lead to flowering and poor winter survival as well (Clark, 2007). Germination for crimson clover and many other clover species was found to be greater than 80% at temperatures between 10°C and 30°C (Brar et al., 1991). Common seeding rates are between 17-20 kg/ha drilled or 25-34 kg/ha broadcast interseeded (Clark, 2007). Crimson clover seldom survives harsh winter temperatures (Curran et al. 2018). Brandsaeter and Netland (1999) found that crimson clover was unable to survive the winter in an experiment conducted in Norway.

Crimson clover can produce between 2200-5600 kg/ha of biomass according to Managing Cover Crops Profitably (Clark, 2007). In a trial conducted in the Netherlands, crimson clover was planted on May 7th and harvested 98 days later produced 6340 kg/ha of biomass, indicating growth over the summer can be greater than that of fall and spring winter annual growth (Den Hollander, 2007). In Georgia crimson clover produced between 4500 and 5000 kg/ha of dry matter when seeded at 25 kg/ha, planted in October or November, and harvested in May or June (Hargrove, 1986). In another Georgia experiment (Schomberg et al., 2006), crimson clover produced 3786 kg/ha of biomass when planted in the fall and biomass harvested in the spring. More recently, Fleming and Thomason (2015) stated that crimson clover produced 3500 kg/ha of biomass after growing for 800 GDDs in a growth chamber under consistent 24°C days and 13°C nights. The relative growth rate of crimson clover was determined to be 0.092 g/g/day which was low in comparison to other clover species, including alsike, berseem, Persian, red subterranean, and white clovers (Den Hollander, 2007).

Crimson clover is described as having an erect growth habit and was found as a weed in the understory of pecan orchards, so it may be shade-tolerant (Bugg et al., 1991). Watson et al. (1984) conducted an experiment in Mississippi using shade chambers providing 50% and 25% of natural light. "Chief" crimson clover density was reduced by over 50% when shade was applied at either level. "Tibbee" crimson clover was unaffected by shade in terms of density. Biomass in 50% and 65% shade was reduced by 40% and 65%, respectively. Plant height was also reduced by over 50% by both shade levels. Van Sambeek et al. (2007) found that biomass reduction of crimson clover under 55% and 80% shade levels was less compared with subterranean clover, red clover, berseem clover, alsike clover, white clover, and arrowleaf clover. Finally, Williams (1963) studied competition for light between subterranean clover, rose clover, and crimson clover. Species were planted in 1:1 mixtures totaling 2500 plants/m^2. Crimson clover produced the greatest LAI at 0.27 by 28 days after planting, compared with 0.18 and 0.16 for rose clover and subterranean clover, respectively. Crimson clover and rose clover both had more erect growth habits compared with subterranean clover, which was very prostrate in growth. Crimson clover always produced the most biomass when in mixture with another clover species (Williams, 1963). This indicates that while crimson clover biomass is reduced with shading and competition, it may be a more shade-tolerant species than other clovers and could be useful as an interseeded cover crop.

Use in Interseeding

In Managing Cover Crops Profitability, crimson clover is rated as excellent for interseeding (Clark, 2007), and crimson clover has been included in many interseeding experiments. In Quebec, crimson clover interseeded at 22 kg/ha into 11-cm and 30-cm tall corn was competitive with corn at the earlier interseeded timing, which the authors attribute to its rapid establishment and growth (Abdin et al., 1998; Abdin et al., 1997). Curran et al. (2018) interseeded crimson clover at 22.4 kg/ha in corn at the V5-V6 growth stages. Crimson clover established successfully in this experiment in New York, Pennsylvania, and Maryland when seeded in mixtures with hairy vetch, red clover, and annual ryegrass, however, its specific biomass was not measured. In Ontario, 13 kg/ha crimson clover was interseeded into sweet corn and seed corn at V4-V6 and V10-V12 (Belfry and Van Eerd, 2016). Crimson clover produced 507 kg/ha of fall biomass, which was greater than red clover but lower than oilseed radish and cereal rye. Corn grain yield was unaffected. In South Dakota, a mixture of crimson clover, lentil, and winter wheat at 5, 9, and 8 kg ha^{-1}, respectively, were interseeded at either V3 or V5 corn (Bich et al., 2014). This mixture did not affect corn grain yield.

Effects on N Cycling

Crimson clover is a legume that forms symbiotic relationships with *Rhizobia* to produce nitrogen. Clark (2007) stated that a N credit of 80-170 kg N/ha should be given for the following crop depending on biomass production. Crimson clover is also considered to be an N scavenger (Clark, 2007). When cover crops were seeded following corn and soybean harvest and soil sampled the following April, soil inorganic N was greater in crimson clover plots compared with the control plots and cereal rye plots, but soil inorganic N was lower compared with the cereal rye + hairy vetch treatment (Chu et al., 2017). In contrast, Belfry and Van Eerd (2016) found that N content in crimson clover was 15.5 kg/ha in the fall, which was significantly higher than in red clover (13.5 kg/ha) indicating that crimson clover uptakes much less N than oilseed radish (70 kg/ha) and cereal rye (24 kg/ha) which also do not produce their own N. In a Georgia experiment, crimson clover seeded in October (seeding rate not listed) had the lowest C:N at 16.4 compared with oilseed radish and cereal rye. Crimson clover plots also had the highest mineralizable N 90 days after termination at 208 kg/ha compared with radish (202 kg/ha) and rye (172 kg/ha). This N is available for plant uptake but also for loss by leaching and denitrification (Schomberg et al., 2006). Dyck and Liebman (1994) conducted a double-cropping experiment in Maine. Crimson clover was seeded in May at 84 kg/ha. Results showed that crimson clover biomass was equivalent to 125 kg/ha of applied N, but it did not affect the double-cropped corn. So, although crimson clover has a low C:N and could provide N to the following crop, the timing of N release likely plays an important role in whether the following crop will benefit.

Other Clover Species

There are many species of clover that are used primarily as cover crops and forages. These include, but are not limited to, red clover (*Trifolium pretense*), berseem clover (*Trifolium alexandrinum*), white clover (*Trifolium repens*), subterranean clover (sub clover; *Trifolium subterraneum* L.), and Persian clover (*Trifolium resupinatum*). Clover species are best known for their N-fixing capabilities with *Rhizobia* bacteria and for their low C:N that often leads to an N credit for the following crop (Clark, 2007). Research has been conducted on many of these clover species as single species or in combination with other clovers and will be compared with crimson clover in this literature review.

Establishment, Biomass, and RGR

Clark (2007) states that red clover and subterranean clover produce up to 2200-5600 kg/ha and 3900-9000 kg/ha of aboveground biomass, respectively, with red clover being similar to crimson clover and subterranean clover producing potentially greater biomass. Den Hollander et al. (2007) performed an experiment in the field, greenhouse, and growth chamber to examine biomass production and RGR of various clover species over a 98-day time period. The species, biomass production and RGR are listed in Figure 1.01. Alsike and crimson clover produced the greatest biomass; however, the relative growth rate of these clover species was the slowest because they produced the most biomass, so the RGR of g of biomass accumulated compared with the original weight was smaller, and second, these species grew to their maximum size slower than the other species. Persian clover was the fastest species to establish while subterranean clover was the slowest. Final emergence percentages were 7, 41, 35, 50, 21, 36, and 7 for alsike, berseem, crimson, Persian, red, subterranean, and white clover, respectively. Persian clover reached maximum emergence at 8 days after seeding and red clover reached maximum emergence at 13 days after seeding. All other species reached maximum emergence around 11 days after seeding (Den Hollander, 2007).

Light and Shade Effects

Shading is an important consideration for interseeding cover crops. Red clover biomass was reduced in an interseeding experiment when corn density increased from 37,500 to 75,000 seeds/ha, suggesting competition for light or another resource (Baributsa et al., 2008). Red clover dry biomass was reduced by 39% and 70% under 50% and 80% shade, respectively (Lin et al., 1999). For subterranean clover, 80-90% of biomass production was retained under 50% shade (Hagedorn 1980, in Knight et al., 1982). In Watson et al. (1984), subterranean clover varieties differed in their response to shade in Mississippi. Shade cloths were placed over field plots in October directly following seeding and removed at harvest in May. Biomass production was between 37% and 92% of unshaded yield in 50% shade. In 75% shade, only 24-49% of biomass was retained. Variety "Nangeela" was consistently the most shade tolerant. Persian clover retained 58% and 36% of yield in 50% and 75% shade, respectively. Berseem clover retained 88% and 56% of yield in the two shade levels. This experiment indicates that certain varieties of clovers within a species may perform better or worse under shade and that berseem clover and subterranean clover had the greatest potential to retain yield under shade; in this experiment, clovers were shaded for 7 months. Mauro et al. (2011) studied the effects of shading on chlorophyll and photosynthesis of subterranean clover under 0%, 40%, 60%, and 90% PAR reduction over a 70-90 day period. Shading caused a reduction in chlorophyll content, photosynthetic rate, and biomass, while chlorophyll fluorescence, specific leaf area, and carbon content in the leaves increased (Mauro et al., 2011). In an interseeding system, maximum shade occurs for about 60 days from July to September, so clovers may be better able to survive and produce biomass under a shorter shaded period.

Multiple studies have examined the effects of shading on white clover. Weijschede et al. (2006) evaluated the shade tolerance of 34 genotypes of white clover under 80% PAR, 20%, and a vertical gradient of PAR ranging from 17%-20%. Average biomass decreased from 0.9 g/plant to 0.4 g/plant to 0.2 g/plant in the 80%, 20%, and gradient light environments, respectively, after 34 days in shade. Petiole length and leaf area both increased and biomass to the petioles increased with increasing shade. Biomass allocation to stolons and roots decreased with increasing shade (Weijschede et al., 2006). Marcuvitz and Turkington (2000) studied the effects of shading and competition from grass species on white clover. Annual ryegrass and two other grasses were clipped to 20-cm tall for the duration of the experiment and grown in 2 rows with a row of white clover in between. Light penetration at midday was nearly equal to the control at

100%, while penetration in the afternoon was lowest at 10-15% of the control. R:FR was reduced to 0.6 during the afternoon from greater than 1 at midday. Shading reduced stolon length, aboveground biomass, and branching. Petiole length was increased with shading from grass species (Marcuvitz and Turkington, 2000). Finally, Solangaarachchi and Harper (1987) grew white clover under shade of plastic black leaves and white clover leaves floating in water. PAR reduction levels were 45-50% and 25-30%. Under shade, petioles and leaf area were increased. In these experiments, white clover responds to shade by increased petiole length and leaf area in an attempt to reach more PAR.

Nitrogen Cycling

Red clover and subterranean clover are given 80-170 and 85-225 kg N/ha credit, respectively, compared with crimson clover's N credit of 80-145 kg/ha (Clark 2007). Den Hollander (2007) seeded different clover species in May and harvested 98 days after seeding. Alsike clover, Persian clover, red clover and white clover had total tissue N contents of greater than 3%, while crimson clover, berseem clover, and subterranean clover had total N contents of less than 3%. Grabber et al. (2014) measured residual NO_3 content in the soil from red clover drill interseeded into corn. Corn planting was on May 9th and cover crops were seeded June 11th. Red clover was seeded at 14 kg/ha and fall nitrate samples were collected in October. Plots with red clover had 6.2 kg NO_3/ha. The authors indicate that N applied to the crop was responsible for the higher N in corn (Grabber et al., 2014). Comparing red clover interseeded in corn that was 0.15-0.3 m tall with red clover seeded at mid-silk, the two timings contained 81 kg N/ha and 12 kg N/ha, respectively (Scott et al., 1987). This indicates that the earlier seeded red clover performed better than the later seeding. Also, corn yielded higher when red clover was plowed under compared with unfertilized corn (Scott et al., 1987). In another experiment evaluating red clover, red clover seeded in March had tissue N levels of 70 kg N/ha in October and 72 kg N/ha the following spring (Vyn et al., 2000). In November, soil NO_3 content was lowest (2.5 mg/kg) with red clover compared with rye and oilseed radish. In the spring, cereal rye had the lowest soil NO_3, but corn yield was increased in plots where red clover was sown the previous spring. This indicates an N credit from the red clover (Vyn et al., 2000). In Hill et al. (2016) red clover increased soil inorganic N by up to 55 kg/ha which increased dry bean grain N but delayed maturity. Finally, in Coombs et al. (2017) red clover broadcast into oats in June and July had 3.7% N content while crimson clover seeded at the same time had significantly lower N content at 3.0%.

Use in Interseeding

Clark (2007) lists crimson, red, and white clovers as good choices for interseeding into other crops. Abdin et al. (1997, 1998) interseeded red clover and white clover in mixtures with annual ryegrass at 10 and 7 kg ha^{-1}, respectively at two timings when corn when 11 and 30 cm tall. The annual ryegrass seeding rate was 8 kg/ha in both mixtures. Subterranean clover at 12 kg/ha, Persian clover at 10 kg/ha, crimson clover at 22 kg/ha, and berseem clover at 20 kg/ha were also interseeded as single species. Only crimson clover interseeded at 11-cm tall corn caused a reduction in corn grain yield (Abdin et al., 1997, 1998. In Michigan, red clover at 20.4 kg/ha was interseeded in grain corn in late May and early June (Baributsa et al. 2008). Corn was planted at 37,500, 55,000, 65,000, and 75,000 seeds/ha in 76-cm rows. Red clover did not reduce corn grain yield, but increased corn density reduced red clover biomass (Baributsa et al. 2008). Cover crops were harvested between late August and early October depending on the year.

Aboveground biomass production per day (Mg/ha/day) averaged 0.036, 0.0044, 0.0052, and 0.0031 when corn density (plants) was 37,000, 55,000, 65,000, and 75,000, respectively. Curran et al. (2018) interseeded red clover into corn at V5-V6 in a mixture with crimson clover and hairy vetch at 11, 22, and 17 kg/ha, respectively, and a mixture with crimson clover, annual ryegrass, and hairy vetch, at 6, 11, 11, and 8 kg/ha, respectively. Biomass was increased when legumes were added compared with annual ryegrass seeded alone. Total biomass ranged from 48 to 1158 kg/ha in the fall and 190 to 2468 kg/ha in the spring when ryegrass was included. Exact biomass numbers were not reported for the mixture without annual ryegrass, but biomass was of this mixture was lower compared with the annual ryegrass mixture. Also, red clover and crimson clover produced more biomass compared with hairy vetch in the mixtures. The authors noted that a legume is preferable for interseeding if N is limited in the system. In another study, researchers interseeded a mixture of alfalfa, yellow sweet clover, red clover and alsike clover in a 19 kg/ha mixture (individual species not noted) into corn at the time of corn planting and at the time of the last cultivation for weeds (Exner and Cruse 1993). Alfalfa and sweet clover established better than red clover and alsike clover. Corn yields were only reduced at the early interseeding timing when weeds were not controlled (Exner and Cruse, 1993). Grabber et al. (2014) interseeded red clover at 13.4 kg/ha into corn planted May 9th in 72-cm rows at 82,000 seeds/ha. The interseeding date was June 11 and it was a drilled seeding. Corn grain yields were not affected by the red clover, and red clover biomass was 2000 kg/ha when harvested in September. In Scott et al. (1987), red clover was interseeded (seeding rates not listed) when corn was 0.15-0.3 m tall and at midsilk. Corn yield was not reduced by the interseeding, and red clover produced a maximum of 55% groundcover in the fall and 62% in the spring. Aboveground biomass of red clover harvested in the fall after interseeding was 2010 kg/ha when seeded at 0.15-0.3 m tall corn and 221 kg/ha when seeded at midsilk. This indicates that early interseeding is required for successful biomass production by red clover. Finally, Noland et al. (2018) evaluated different interseeding methods using red clover (13 kg/ha) seeded at V7 corn. Fall biomass was higher for the drilled and broadcast + incorporated seedings compared with the broadcast seeding. Per seeding method, red clover produced the greatest fall biomass.

Cover Crop Mixtures

Seeding mixtures of multiple species of cover crops combines the benefits of the single species in the mixture (Clark, 2007). Potential advantages of cover crop mixtures include improved winter survival, ground cover, solar radiation capture, biomass production, N cycling, weed control, and duration of the growing period compared with monocultures (Clark, 2007). When discussing cover crop mixtures, much of the literature focuses on: a) biomass compared with a monoculture; b) weed suppression compared with a monoculture; c) dominant species in the mixture; and d) nitrogen dynamics compared with a monoculture.

Faurie et al. (1996) evaluated a 50:50 mix of annual ryegrass and white clover. Under adequate N and water supplies, radiation use efficiency of white clover was lower than that of annual ryegrass. In natural settings without additional N and irrigation, white clover captured more PAR than perennial ryegrass, but adding additional N reduced this competitive advantage. Radiation use efficiency was higher for both species when stressed, i.e. when perennial ryegrass was N-limited, and when white clover was disadvantaged by N additions (Faurie et al., 1996). This research explains why grasses may dominate multispecies mixtures when N is not limited.

Finney et al. (2016) reported biomass production and C:N influences on ecosystem services for cover crop mixtures in an experiment in Pennsylvania. Cover crops included sunn hemp (22 kg/ha monoculture; 11 kg/ha mixture); soybean (90 kg/ha monoculture; 45 kg/ha mixture); forage radish (11 kg/ha monoculture; 3 kg/ha mixture); red clover (13 kg/ha monoculture; 5 kg/ha mixture); hairy vetch (28 kg/ha monoculture; 11 kg/ha mixture); canola (12 kg/ha monoculture; 5 kg/ha mixture); cereal rye (134 kg/ha monoculture; 67 kg/ha mixture); barley (54 kg/ha mixture); and annual ryegrass (16 kg/ha mixture). Cover crops were seeded after oat in August and biomass was sampled in the fall and in May. Soil NO_3 content was measured in the fall, and inorganic N was measured biweekly throughout the following corn cash crop season. Results showed that increasing the number of species in a stand increased total biomass but combining cover crops of the same function did not increase biomass (e.g. legume + legume) compared with a monoculture. Increased cover biomass did increase weed suppression. For N dynamics, nitrate leaching was reduced with increasing biomass and aboveground shoot N content; however, soil inorganic N, and therefore corn N availability, decreased with increasing cover crop biomass. These authors also indicated that functional diversity was more important than species diversity (Finney et al., 2016).

Another experiment studied the effects of legume/non-legume mixtures on multifunctionality in agroecosystems (Finney and Kaye, 2016). Cover crop species included oat, canola, sunn hemp, soybean, barley, perennial ryegrass, forage radish, cereal rye, millet, sorghum sudangrass, red clover and hairy vetch (seeding rates are listed in Finney et al., 2016). Seven, four-species mixtures and two, eight-species mixtures were planted in late August and terminated prior to corn planting in May. Aboveground biomass was measured about 55 days after sowing, NO_3 in the soil was measured throughout the fall, and biweekly measurements of ammonium and nitrate were taken throughout the following corn season. Cereal rye often dominated the mixtures in terms of biomass production. Increasing species richness increased weed suppression, N retention in the soil, and aboveground biomass N; however, species richness negatively affected inorganic N availability to the corn crop during the growing season, and there was no effect on corn grain yield. The researchers concluded that increased species richness did not increase multi-functionality and that functional diversity should be emphasized when choosing mixtures (Finney and Kaye, 2016).

Research from Iowa studied cover crop mixtures planted prior to corn and soybean (Licht et al., 2017). Oat was planted prior to corn as a single species and in a mixture with hairy vetch, and radish (seeding rates not listed). Cereal rye was planted prior to soybean as a single species and in a mixture with rape and oilseed radish. Corn grain yields were unaffected by single species or mixtures. For biomass, oat as a single species had greater or equal biomass to the mixture in 12 of the 14 site years prior to corn. Cereal rye as a single species had greater biomass in 3 of 4 site years compared with the mixture prior to soybean, and soybean yield was unaffected (Licht et al., 2017).

Murrell et al. (2017) evaluated the effects of planting date and seeding rate on cover crop mixture dynamics. Cover crops were seeded in August after wheat or in October after corn as monocultures and in 3-, 4-, and 6-species mixtures. Red clover seeding rates were 600 plants/m^2, 300 plants/m^2, and 150 plants/m^2 as a monoculture, in the 3- and 4-species mix, and in the 6-species mixture, respectively. Canola seeding rates were 400 plants/m^2, 200 plants/m^2, and 100 plants/m^2 as a monoculture, in the 4-species mix, and in the 6-species mixture, respectively. Forage radish seeding rates were 60 plants/m^2, 50 plants/m^2, and 20 plants/m^2 as a monoculture, in the 3- and 4- species mix, and in the 6-species mixture, respectively. Cereal rye seeding rates were 500 plants/m^2, 100-250 plants/m^2, and 100 plants/m^2 as a monoculture, in the 3-species mix, and in the 4- and 6-species mixture, respectively. Oat seeding rates were 300 plants/m^2, 150 plants/m^2, and 75 plants/m^2 as a monoculture, in the 3-species mix, and in the 6-species mixture, respectively. Austrian winter pea seeding rates were 60 plants/m^2, 30 plants/m^2, and 15 plants/m^2 as a monoculture, in the 3- and 4- species mix, and in the 6-species mixture, respectively. Oat, pea, and canola often had high biomass in the fall compared with the other species, while red clover had little biomass in the fall. Cereal rye biomass was dominant in the spring, especially when planted after corn, as it is one of the only species with highly successful establishment at that time. Cereal rye also caused other species to die out by the spring. Biomass in the mixtures was comparable to that of the monocultures. The authors recommend lowering seeding rates of grasses in mixtures and avoiding seeding mixtures after summer due to poor establishment (Murrell et al., 2017).

Smith et al. (2014) evaluated cover crop mixtures in New Hampshire to determine if mixtures were more productive than monoculture cover crops. Cover crops included buckwheat (67 kg/ha), mustard (7 kg/ha), sorghum-sudangrass (34 kg/ha), cereal rye (112 kg/ha), one year of hairy vetch (44.8 kg/ha), and the other year of field pea (224 kg/ha). A mixture of all species was included at 20% of their respective seeding rates. The cover crops were seeded in June and harvested at 43 and 72 days after planting in different years. In the first year, buckwheat produced the highest biomass of 2500 kg/ha compared with all monocultures and the mixture which produced about 1000 kg/ha. In the second year, sorghum-sudangrass produced 7200 kg/ha of biomass while the mixture produced 4500 kg/ha, which were both higher than mustard and cereal rye monocultures. Weed suppression nor cash crop productivity were enhanced by the cover crop mixture (Smith et al., 2014).

Ranells and Wagger (1997) evaluated winter annual legume monoculture and grass-legume bicultures on aboveground dry matter and N accumulation as well as their effects on soil inorganic N. Austrian winter pea was seeded at 60 kg/ha in monoculture and 45 kg/ha in biculture; crimson clover was seeded at 34 kg/ha in monoculture and 22 kg/ha in biculture; common vetch was seeded at 28 kg/ha in monoculture and 22 kg/ha in biculture; and hairy vetch was seeded at 28 kg/ha in monoculture and 22 kg/ha in biculture. Cereal rye, oat, and wheat were seeded at 56 kg/ha in mixtures with each of the other non-grass species. Cover crops were planted in October and harvested in April. Overall, biomass of legumes was greatly reduced when in the mixture with grass. In 2 of 3 years, biomass of legumes + grass was greater than legumes alone. For N content, crimson clover had the lowest shoot N content each year while Austrian winter pea had the highest. C:N was usually higher in the grass-legume mixtures compared with legume monocultures. Finally, corn grain yields were reduced in 2 of 3 years, and the authors attributed this to high grass biomass impeding early corn growth (Ranells and Wagger, 1997).

Hayden et al. (2014) evaluated the relative proportions of cereal rye and hairy vetch sown in mixtures. Seeding rates of the mixtures included hairy vetch and cereal rye, respectively, at 42 kg/ha + 0 kg/ha; 35 kg/ha + 16 kg/ha; 28 kg/ha + 31 kg/ha; 21 kg/ha + 47 kg/ha; 14 kg/ha + 63 kg/ha; 7 kg/ha + 78 kg/ha; and 0 kg/ha + 94 kg/ha. Cover crops were seeded on September 1 and harvested in May. The authors found that there was little interspecific competition between the two species. Shoot biomass was usually greater for mixtures compared with single species. Maximum spring biomass was achieved with the 35 kg/ha + 16 kg/ha of hairy vetch and cereal rye, respectively, while minimum biomass was seen with the 94 kg/ha of cereal rye monoculture. Furthermore, as rye percentage increased, light penetration through the canopy increased; however, weed suppression was greater with increasing amounts of cereal rye. For N content, hairy vetch shoot N content was 18 g/m^2 in the monoculture. For all other N contents, the mixtures were greater than the monoculture of cereal rye (Hayden et al., 2014).

Brainard et al. (2012), examined the effects of hairy vetch grown alone and in mixture with cereal rye on overwinter survival, biomass production, biological nitrogen fixation (BNF), and the yield of the following sweet corn crop. Hairy vetch was seeded at 45 kg/ha in monoculture and at 22.5 kg/ha in a mixture with cereal rye at 62.5 kg/ha. Cover crops were seeded in September and terminated in May. Seeding hairy vetch with cereal rye increased the winter survival of hairy vetch. Biological nitrogen fixation was increased in one hairy vetch variety when seeded with rye. For biomass, the mixtures always produced greater biomass (7000 kg/ha) than hairy vetch in monoculture (4000 kg/ha), but cereal rye comprised up to 75% of the mixture. Shoot N content of hairy vetch ranged from 40-60 kg/ha in the mixture and about 80 kg/ha in the monoculture. Rye N content in the mixture was about 20-30 kg/ha. Soil N content had a wider range from 20-70 kg/ha from the hairy vetch monoculture and 10-20 kg/ha from the mixture (Brainard et al., 2012).

Chu et al. (2017) studied the effects of cover crop mixtures on soil properties and crop yield. Cereal rye + hairy vetch, cereal rye + crimson clover, and cereal rye + oats + daikon radish + turnips + crimson clover (rates not given) were seeded following corn and soybean in October and sampled prior to termination in March/April the following spring. Soil inorganic N and mineralizable N was measured in October after 3 years of the experiment. Soil inorganic N content was reduced in the control and cereal rye monoculture plots only. Potentially mineralizable N was highest in the 5-species mixture and the cereal rye + crimson clover treatments at nearly 50 mg/kg, while wheat was the lowest at about 40 mg/kg. Soybean yield increased by 0.5 Mg/ha after three years of cover cropping with the 5-species mixture. There were no other changes in soybean yield nor in yield in the first two years of the experiment (Chu et al., 2017).

Nielsen et al. (2015) studied the differences in water use of cover crop mixtures compared with monocultures in Colorado. Cover crops were planted during the fallow year in April and terminated in June or July. Monocultures included rapeseed (7.4 kg/ha), oat (94 kg/ha), and pea (114 kg/ha). A mixture of oat (13.7 kg/ha), pea (8.9 kg/ha), lentil (5.9 kg/ha), common vetch (4.7 kg/ha), berseem clover (1.2 kg/ha); barley (12.5 kg/ha), phacelia (2.3 kg/ha), and safflower (3.5 kg/ha) was also seeded. Soil water content was not significantly different between single species and the mixture. Cover crop water use was 216 mm compared with evaporative water loss of 122 mm in the bare ground fallow. This increased water use could be detrimental to crop production in arid regions (Nielsen et al., 2015).

Wortman et al. (2012) also evaluated cover crop mixtures in Nebraska for the Western Corn Belt. Single species included hairy vetch (45 kg/ha), Idagold mustard (13 kg/ha), field pea (112 kg/ha, Pacific gold mustard (9 kg/ha), crimson clover (28 kg/ha) oilseed radish (17 kg/ha), chickling vetch (67 kg/ha, and dwarf essex rape (14 kg/ha). Mixtures included hairy vetch (11.2 kg/ha) + Idagold mustard (6.7 kg/ha); hairy vetch (11.2 kg/ha) + Idagold mustard (3.4 kg/ha) + field pea (28 kg/ha) + Pacific gold mustard (2.2 kg/ha); hairy vetch (7.5 kg/ha) + Idagold mustard (2.2 kg/ha) + field pea (18.7 kg/ha) + Pacific gold mustard (1.7 kg/ha) + crimson clover (4.7 kg/ha) + oilseed radish (2.8 kg/ha); and hairy vetch (5.6 kg/ha) + Idagold mustard (1.7 kg/ha) + field pea (14 kg/ha) + Pacific gold mustard (1.1 kg/ha) + crimson clover (3.5 kg/ha) + oilseed radish (2.1 kg/ha) + chickling vetch (8.4 kg/ha) + dwarf essex rape (1.7 kg/ha). Cover crops were planted in March and harvested in May. Mustard crops produced 2400 kg/ha of biomass on average compared with legumes which produced 1200 kg/ha on average. Using the

Land Equivalent Ratio, mixtures were slightly more productive than monocultures; though they did not produce greater biomass compared with brassicas alone. Brassicas dominated the mixtures, but legumes in mixtures could provide an important source of N (Wortman et al., 2012).

Tribouillois et al. (2015) determined if a crop model could be used to predict biomass and N production in cover crop mixtures. The experiment examined mixtures of legumes + non-legumes under natural conditions, and 34 monocultures under irrigated and N-fed conditions. Non-legume crops were generally more competitive in the mixtures, and functional traits were of greater importance than species diversity to ecosystem services. Also, water and N availability influence species dominance within a mixture. For example, non-legume crops are less dominant when N is limiting compared with legume species (Tribouillois et al., 2015).

Couedel et al. (2018a) studied the S-capture and S green manure service of brassica-legume mixtures, and Couedel et al. (2018b) studied N-capture and N green manure services of the same mixtures. Brassica species included rape (80 plants/m^2), white mustard (100 plants/m^2), Indian mustard (100 plants/m^2), Ethiopian mustard (150 plants/m^2), turnip (80 plants/m^2), turnip rape (80 plants/m^2), oilseed radish (80 plants/m^2), and yellow rocket (100 plants/m^2). Brassicas were seeded in mixtures with legumes which included Egyptian clover (100 plants/m^2), purple vetch (100 plants/m^2), common vetch (100 plants/m^2), hairy vetch (100 plants/m^2), crimson clover (70 plants/m^2), soybean (70 plants/m^2), faba bean (40 plants/m^2), pea (80 plants/m^2), and lupin (70 plants/m^2). Legumes were also seeded as single species at 800 plants/m^2. Cover crops were seeded following wheat, barley, or a fallow period in August and harvested in October or November. On average, brassica-legume mixtures, and brassicas alone, contained 12 kg S/ha in their aboveground biomass while clovers alone contained only 4 kg S/ha. Brassicas alone provided 6.5 kg S/ha to the soil for the next crop and mixtures provided 5.5 kg S/ha (Couedel et al., 2018a). Biomass N content was 120 kg/ha, 100 kg/ha, and 70 kg/ha for legumes alone, mixtures, and brassicas alone, respectively. Six months after termination, soil mineralizable N was 22 kg/ha from brassica-legume mixtures compared with 8 kg/ha from brassicas alone (Couedel et al., 2018b). These two studies indicate that combining brassicas and legumes can help to provide both S and N to a greater extent than a monoculture of one species or the other.

In summary, biomass in monocultures compared with mixtures is variable. In some experiments, the monoculture biomass was equal to or greater than the mixture, while in others, the mixture produced greater biomass. When a grass, such as cereal rye or annual ryegrass, is present, biomass of mixtures is often dominated by the grass species and biomass is similar comparing monocultures and mixtures. Legume biomass is often severely inhibited in mixtures, especially with an aggressive grass species. It is therefore recommended to greatly reduce seeding rates of grasses in mixtures and to seed mixtures earlier in the season, such as in late summer, to allow for less cold-hardy species including brassicas and legumes to emerge and contribute to the mixture; however, grasses provide nutrient scavenging, are competitive with weeds, and some are winter hardy and provide benefits into the spring, so ensuring adequate grass stands in mixtures is still important. For weed suppression, biomass of the mixture or monoculture seems to be of greater influence than the species themselves, with higher weed suppression often occurring when biomass is high. Grass species tend to dominate mixtures when given adequate N and water; with limited N, grass species growth may be reduced. N dynamics are often mixture-dependent. Legumes in monocultures often produce more N than in mixtures but lack the biomass that brassicas and grasses provide. It is helpful to consider all the functions of the mixture rather than focusing just on nutrient dynamics as the sole benefit.

Finally, the literature generally supports the idea that functionality of a mixture is of greater importance to providing ecosystem services compared with species richness. This is important when considering cover crop species to include in a mixture.

Cover Crop Mixtures in Interseeded Corn

Many cover crop interseeding research to date has also included seeding of mixtures. Abdin et al. (1998) interseeded mixtures including red clover (10 kg/ha) + annual ryegrass (8 kg/ha), and white clover (7 kg/ha) + annual ryegrass (8 kg/ha). While very little information about the cover crops was given in this experiment, corn grain yield was not reduced (Abdin et al., 1998). Curran et al. (2018) interseeded mixtures of red clover (11.2 kg/ha) + crimson clover (22.4 kg/ha) + hairy vetch (16.8 kg/ha) and a mixture of annual ryegrass (11.2 kg/ha) + red clover (5.6 kg/ha) + crimson clover (11.2) kg/ha + hairy vetch (8.4 kg/ha) into corn at the V5-V6 growth stage. The mixture with annual ryegrass produced greater biomass than annual ryegrass as a monoculture. Legumes in the annual ryegrass mixture comprised about 50% of the biomass, while hairy vetch produced very little biomass in the mixture. This experiment noted that annual ryegrass biomass was limited at sites where N was limited and stated that a legume + annual ryegrass mixture would be beneficial for N-limited situations (Curran et al., 2018). Scott et al. (1987) seeded mixtures of red clover + perennial ryegrass and red clover + cereal rye (seeding rates not given). No cover crops in this experiment affected corn grain yield. The mixtures provided the same amount of ground cover as cereal rye in a monoculture (80%), which was higher than any other single species in the experiment (Scott et al., 1987). Another experiment in Iowa interseeded a mixture of alfalfa, yellow sweet clover, red clover, and alsike clover in a mixture at the time of the last cultivation for weeds (Exner and Cruse, 1993). The mixture totaled

19 kg/ha with equal weights of each species. Alfalfa and sweet clover established better than red clover and alsike clover (Exner and Cruse, 1993). Similar to non-interseeded mixtures, grass species, such as annual ryegrass, have the potential to dominate a mixture, especially with adequate N supply. Mixtures, like single species, do not negatively impact corn grain yields when seeded at V3 or later, though weed control may still be an issue. Noland et al. (2018) evaluated different seeding methods on a mixture of hairy vetch, pennycress, red clover, and cereal rye seeded at 140 kg/ha total at V7 corn. Fall biomass was significantly higher for drilled interseeding compared with broadcast and broadcast + incorporation. Fall biomass differences were greatly reduced by compensatory spring growth. The authors explained that larger seeds benefit more from drilled seedings while smaller seeded species may be better suited for broadcast seedings. In this experiment, rainfall was adequate for establishment of all seeding methods; the authors note that with dryer conditions, broadcast seedings are much more susceptible to poor or failed establishment (Noland et al., 2018).

Interseeded Cover Crop Tolerance to Herbicides

If seeding a cover crop in corn in the first eight weeks following corn planting, it is important that weeds are controlled. This is often achieved by the application of soil-applied or postemergence herbicides with residual activity. Very few published studies have evaluated interseeded cover crop tolerance to preemergence herbicides. Wallace et al. (2017) studied the effects of preemergence herbicides on annual ryegrass and red clover interseeded into corn at the V5 growth stage. Annual ryegrass biomass was reduced by S-metolachlor, pyroxasulfone, pendimethalin, and dimethenamid-P. Only mesotrione reduced red clover biomass. None of the grass herbicides nor saflufenacil, rimsulfuron, and atrazine reduced red clover biomass. Other research has focused on cover crops seeded late in corn, but not on early interseeded cover crops.

Climate and Environment

Response of Maize to Changing Temperature and Precipitation

Increased temperatures and greater variability in rainfall patterns are two expected outcomes of climate change across the Midwestern United States. According to the National Climate Assessment (NCA, 2014), average temperatures in the Midwest, including Michigan and Iowa, have risen in the region by about 1°C since 1900. The average temperature in Iowa is expected to increase by about 2.3-2.6°C by 2070, and by 2.4°C to greater than 2.8°C in Michigan. In many areas of the Midwest, precipitation is expected to have from no change annually up to a greater than 10-cm increase. Increases in precipitation are expected to be largely during the winter and spring with less change over the summer and fall. However, precipitation in the summer and fall is expected to occur in fewer, more intense events. This data is based on climate models and could vary greatly but expected trends will affect agriculture moving into the future (NCA, 2014).

Maize is one of the major agronomic crops grown throughout the Midwestern United States, and climate change will undoubtedly affect its production. Shlenker and Roberts (2009) analyzed maize, soybean, and cotton yields under climate change, specifically increasing temperatures. Maize yields increased as temperatures increased to about 30°C. Yields sharply declined as temperatures continued to increase above 30°C (Schlenker and Roberts, 2009). This research included many maize-producing states including Michigan and Iowa. Hatfield et al. (2011) reviewed temperature effects on maize for the Midwestern United States; maize yields were expected to decrease by 2.5% with an increase of 0.8°C. Increasing CO_2 effects are expected to mitigate this to only a 1.5% decrease in yield for an increase of 0.8°C. Evapotranspiration (ET) is expected to increase with increasing temperatures which could induce water stress as well. In a paper published in 2014, Bassu et al. (2014) combined the results of 23 models to predict the effect of increasing temperatures on maize yield. The results showed that temperature had the greatest impact on maize yield with decreasing yield as temperatures increased. In Iowa, average yields decreased from 9.4 Mg/ha to 4.3 Mg/ha with an increase of 9°C. Furthermore, the rate of maize development increased as days to anthesis was reduced by 3.1 days. In 2016, research by Xu et al. (2016) supported Bassu's research results. Xu et al. (2016) used the output of multiple global climate models to predict maize yield in Iowa under reduced CO_2 emissions and high emissions scenarios. Under reduced CO_2 emissions, temperatures increased by 2°C by 2100, and under high emissions, temperatures increased by up to 8°C by 2100. Precipitation predictions were much more variable. Very little change in precipitation were expected for the months of July and August; however, spring and fall precipitation either increased or decreased depending on each model projection. Maize yields were found to be more highly correlated with temperature than precipitation. Under the low emissions scenario, yields decreased 13-15% by the end of the century using a 1700 growing degree day (GDD) cultivar and by up to 50% by the end of the century under high emissions. The authors explained that maize reached maturity faster with higher temperatures resulting in lower yields because the growing season was reduced by 10-34 days. Ultimately, there was a 6% decrease in maize yield for every 1°C increase (Xu et al., 2016). Other researchers published in 2016 on climate change and maize yield in central Iowa (Basche et al. 2016). They predicted a 1.6% decrease in yield per decade for maize. Again, it was explained that temperature increased maize development rates causing reduced yields. Also, higher temperatures increased evapotranspiration (ET), which resulted in greater water stress. This experiment did note that a 25% decrease in rainfall from about 860 mm to 690 mm resulted in reduced yields (Basche et al., 2016). Therefore, with cultivars currently used today, maize yields are expected to decrease, so both cultivar and management changes are necessary to adapt to the changing climate. Lindsey and Thomison (2016) found that when drought conditions occurred, drought tolerant hybrids yielded greater than conventional corn hybrids. In this experiment, conventional hybrids yielded higher than drought-tolerant hybrids when water stress was removed. Drought tolerant hybrids must yield the same in years with ideal growing conditions compared with conventional hybrids, especially as climate change increases precipitation variability.

Climate Change and Soil Water Balance

Precipitation patterns are predicted to change in the future as well as temperatures during the growing season. These changes will influence the soil water balance and impact maize growth during periods of drought. The Soil Water Balance Equation is:

Precipitation + Irrigation = Soil Water Content + Drainage + Runoff + Evapotranspiration

In Iowa, current rainfall amounts are about 860 – 865 mm annually (Basche et al., 2016; Zhiming and Helmers, 2010; NCDC, 2018). Soil water content was 115 mm at the surface and 120 mm up to 60-cm deep Boone county Iowa, where the primary soil type is loam (Basche et al., 2016). Zhiming and Helmers (2010) conducted an experiment in Central Iowa on a primarily loam soil and found that soil water content varied based on land coverage. With no cover, soil water storage was 159 mm up to 60-cm deep; with cereal rye, soil water storage was 180 mm. The authors explained that cereal rye reduced drainage by creating better soil structure and increasing soil water storage. Drainage in this experiment was 424 mm per year on average, which was nearly half of the total rainfall; however, the presence of a cereal rye cover crop reduced drainage. Water that is held in the soil from field capacity to the wilting point is available for plant uptake. Use of water for maize production varies by state and current climatic conditions. Maize in Illinois used about 400 mm of water to produce about 17 Mg/ha of total plant biomass (Hickman et al., 2010). In South Dakota, water use ranged from 306-352 mm for maize producing 12 kg/ha under continuous maize with no N applied to 24 kg/ha under maize-soy-wheat-alfalfa with N applied (Pikul et al., 2005).

A more complete experiment on climate change and the water balance of maize in Iowa for current and future scenarios was completed by Wang et al. (2015). Average annual precipitation increased from 769 mm to 813 mm using six different models. Average annual temperature increased from 8.1°C to 10.3°C. Radiation did not change. CO_2 concentration increased from 369 ppm to 548 ppm from 2009-2064. Actual evapotranspiration increased from 442 mm to 450 mm while potential ET increased from 575 mm to 608 mm. Drainage increased from 290 mm to 332 mm. The WUE of maize decreased from 2.12 kg grain/m^3 water to 1.83 kg grain/m^3 water. Increased temperature was cited as the major reason for maize yield loss (Wang et al., 2015).

At the Kellogg Biological Station (KBS) in Michigan, researchers tested the effects of animal manure, inorganic N and compost on crop productivity, and found that the average drainage was 345 mm per year for a fine loamy soil (Basso and Ritchie, 2005). Annual precipitation in this study ranged from 653 mm to 780 mm over six years. Syswerda and

Robertson (2014) conducted research at the KBS Long-Term Ecological Research plots and found that SWC of fine to coarse loamy soils was 0.13 g water/g soil in no-till management and was 0.11 g water/g soil under conventional management. Drainage was highest in the no-till plots at about 412 mm/year. The authors also found that soil water content was positively correlated with net primary productivity, nitrate leaching and grain yield. For productivity of maize related to water use, Hamilton et al. (2015) analyzed ET and WUE of multiple crops including maize in Michigan. Precipitation ranged from about 700 mm to nearly 1200 mm per year. Maize ET ranged from 469-549 over the four growing seasons of the experiment. Biomass production in maize ranged from 19-27 Mg/ha. Water use efficiency for biomass production ranged from about 30-60 kg/ha/mm of water. In drought years, biomass and WUE was greatly reduced (Hamilton et al., 2015). With climate change and the increased potential for drought, today's maize hybrids may also suffer in respect to their WUE in the future. According to Woznicki et al. (2015), total precipitation for the Kalamazoo Watershed in Southwest Michigan is expected to increase to nearly 1000 mm per year by 2079, although some climate change scenarios predict reductions in precipitation. Total ET is not expected to change much with climate change with a slight decrease from about 475 mm to 450 mm. Deep percolation or drainage through the soil is expected to increase from below 400 mm to greater than 400 mm. Surface runoff averages are below 100 mm and are expected to remain steady. A global experiment that included the Midwest used multiple models found that the global average maize yield of 3.32 t/ha is expected to decrease by up to 0.48 t/ha by 2070 under climate change. ET is also expected to decrease for maize with climate change. The water content of the crops is also expected to decrease (Fader et al., 2010).

Though many models show slight increases in precipitation from climate change, variability in the timing and intensity of rainfall events is of concern; additionally, increased temperatures are expected, and both of these factors will affect the soil water balance. Rainfall into the soil will be variable, but there could be longer periods of drought coupled with very large amounts of precipitation intermittently. Furthermore, coarse soils or soils with low water holding capacity may be more at risk to dry conditions compared with soils that have a larger water holding capacity. Management practices will need to adapt to control runoff and drainage with large rainfall events and conserve soil moisture for the extended dry periods. Increased temperatures will increase evaporative demands by the atmosphere, so improved corn hybrids are required with better WUE to adapt to greater loss of water from the soil through ET.

Irrigated Maize Production

For irrigation of maize, 25 mm of water per three-day dry period is typical (Steele et al., 2000). DeJonge et al. (2007) used 30 mm per three days because that is the amount that allows for 50% soil water depletion. This experiment was conducted in Iowa on loam and silty loam soils. In Michigan, Woznicki et al. (2015) explain that precipitation in the Kalamazoo watershed is expected to increase by 2079, but precipitation is expected to be more variable and less predictable. Demand for irrigation in the SWAT model was near 75 mm for the months of June and July but reduced to between 25 mm and 50 mm by August. Irrigation demand for May and September were about 25 mm. For May, June, and September, irrigation demands are expected to increase compared with current usage while July and August values are expected to decrease. Maize yields from 1980-1999 were between 4.83 t/ha and 5.15 t/ha. Despite adaptation of irrigation, yields decrease to between 4.07 t/ha and 4.75 t/ha. Furthermore, irrigation demands are increased with earlier planting dates that are expected with warmer spring temperatures. Earlier planting may enable maize to pollinate prior to the extreme heat of summer and preserve yields (Woznicki et al., 2015). Another modeling experiment from northwest Ohio found that current precipitation ranged from 448-502 mm during the growing season. Future predictions are variable with changes ranging from a decrease of 29 mm to an increase of 37 mm of precipitation. For every scenario, potential ET is expected to increase. Currently, two of three locations benefitted from subsurface irrigation. With future climate change, all sites show a benefit of using subsurface irrigation on maize yield (Gunn et al., 2018). Finally, Islam et al. (2012) studied the effects of climate change on irrigated maize yield. Three levels of irrigation, 100%, 75%, and 50%, of crop ET demand were used to study WUE under deficit irrigation. Temperatures used in the model included increases of 1.4-1.9, 2.1-3.4, and 2.7-5.4°C which are predicted in the future. The model also included reductions in precipitation as is expected in this region of Colorado with climate change. Regardless of irrigation level, yield was reduced because of temperature increases. Yield decreases were greatest for 100% ET because it had the highest base yield. Yield reductions were as high as 35% by 2080 (Islam et al., 2012). Irrigation will likely be increasingly important with climate change as greater precipitation variability is expected. Improved hybrids with greater WUE are needed in these systems to help conserve the limited water resource while still growing highly productive crops.

Cover Crops and Climate Change

Cover crops are affected by, and have the ability to mitigate, climate change. One experiment in Georgia studied the water use efficiency of maize grown with a white clover living mulch (Sanders et al., 2018). Under drought conditions in one year, WUE was reduced with the presence of a cover crop. Also, cover crop residue preserved soil water content compared with a living mulch. This indicates that terminated cover crops may protect the soil from water loss, whereas, a living mulch may compete for water when water is limited (Sanders et al., 2018). This is especially important to consider in an interseeded cover crop system with climate change if precipitation is reduced. In Zhiming and Helmers (2010), cereal rye increased soil water storage from 159 mm (no cover) to 180 mm at the 60-cm depth. The authors explained that cereal rye reduced drainage by creating better soil structure and increasing SWC. Drainage in this experiment was 424 mm per year on average, which was nearly half of the total rainfall; however, the presence of a cereal rye cover crop reduced drainage indicating that cover crops may be used to conserve water in the soil with extended periods of drought.

Crop residue on the soil surface or a cover crop such as cereal rye may reduce runoff following rainfall events. In Iowa runoff increased as the amount of rainfall increased (Elhakeem and Papanicolaou, 2009). Runoff from a 20-mm rainfall event was between 10 to 20 mm, whereas runoff for an 80-mm rainfall event ranged from about 20 to 50 mm based on land use type. In an experiment modeling runoff from 2040-2059 in the Midwest, runoff increased by 10% to 300% (O'Neal et al., 2005). The increases in runoff were explained by reduced maize yields resulting in reduced biomass cover to prevent runoff as well as increased precipitation and intensity of precipitation. In another modeling experiment, runoff in Iowa did not increase with a 7-mm increase from 84 mm to 91 mm under climate change (Schilling et al., 2008). Therefore, cover crops can be used to increase water infiltration and prevent water loss by runoff.

Finally, Kaye and Quemada (2017) explain that cover crops have the ability to mitigate global warming. Cover crops reduce CO_2 fluxes by 100-150 g CO_2 e/m^2/year, which is higher than mitigation with no-till alone. Furthermore, cover crops increase the albedo of surfaces compared with a bare soil surface and can reduce the heat absorbed by the earth's surface. For cover crops that provide a N credit to the following crop, less N fertilizer is used which reduced greenhouse gases through fertilizer production. Also, cover crops create a microclimate above the soil with cooler temperatures and less wind that reduces the evaporative demand. Overall, the authors point out that cover crop effects on climate change mitigation outweigh their negative impacts on climate change, which include more passes over the field with fossil fuel-burning equipment and stimulation of microbial communities which leads to greater CO_2 release from the soil and denitrification and N_2O production (Kaye and Quemada, 2017).

The current research shows that cover crops have the potential to be used to improve soil water holding capacity and prevent water loss through runoff, drainage, and increased ET. This knowledge is crucial for managing water as climate change causes greater variability in precipitation frequency and intensity. Cover crops can also be used to mitigate climate change by reducing greenhouse gas emissions, though they are only one practice of many that will be needed.

Response of Cover Crops to Changing Temperature and Precipitation

There is limited published research on the effects of climate change, and specifically temperature and precipitation, on cover growth. Biomass of a cereal rye cover crop in Iowa increased from 1100 kg/ha to 1400 kg/ha from 2020 to 2060 with increasing temperature and precipitation (Basche et al. 2016). The increased rye biomass did not result in a maize yield reduction. Another experiment studied the water and nitrogen balances in a Mediterranean climate under irrigation as affected by cover crops using the Water and Agrochemicals in the soil and Vadose Environment (WAVE) model. The cover crops used were barley and vetch with a fallow period in rotation with maize. Cover crop biomass in the spring ranged from 3000 to 9000 kg/ha with progressive harvest dates in the spring. Cover crops transpired 20 mm of water when biomass was 3000 kg/ha and up to 120 mm of water when biomass was 9000 kg/ha. The WAVE model also showed that increasing temperature increased cover crop biomass in the spring. A 2°C increase in temperature nearly doubled cover crop biomass from 6000 kg/ha to 11,500 kg/ha. When water was not limiting, transpiration increased linearly and is equal to 10 mm per increase in 1°C on average. Deep percolation of water increased with increasing temperature and increasing precipitation and was higher in fallow than when there were cover crops. This trend also occurred for nitrate leaching (Alonso-Ayuso et al., 2018).

Rainfall timing and intensity is also important to cover crop success. Exner and Cruse (1993) noted that heavy rainfall damaged cover crop seedlings on the soil surface. If rainfall events become more intense with climate change, this could be a factor in cover crop establishment; however, in an interseeded system, corn may provide a barrier to protect the cover crops from heavy rainfall. For aerial seedings of cereal rye into corn, rainfall after interseeding was determined to be the most important factor for establishment (Collins and Fowler, 1992; Wilson et al., 2014). Also, Knight et al. (1982) found that rainfall within a month of seeding a cover crop was essential to produce good cover crop stands.

For annual ryegrass, Gramshaw et al. (1976) studied annual ryegrass germination under different temperature and light regimes. Germination was fastest at 23°C at just under two days to 50% germination; as temperatures increased to 35°C and decreased to 8°C, time to 50% germination decreased to greater than two days and six days, respectively. The highest germination percentage occurred at 27°C. Therefore, under summer conditions in Michigan, which average about 14°C minimum and 27°C maximum temperatures for June and July, annual ryegrass should have a high rate and percentage of establishment. Constantin et al. (2015) found that 34.6°C was the maximum temperature for annual ryegrass emergence. If temperatures increase to high levels as projected for some areas of MI by 2070, germination of annual ryegrass could be inhibited, especially for annual ryegrass in an interseeded system which is seeded early in the summer as temperatures begin to rise. Jiang and Huang (2001) studied heat tolerance of perennial ryegrass at high temperatures (35°C day/30°C night). Photosynthetic rate, photosynthetic efficiency, and leaf water content was reduced for perennial ryegrass even when water was not limiting. Root biomass and length was reduced as well. In order to survive summer stress under increasing temperatures due to climate change, perennial ryegrass must be able to maintain these measured parameters (Jiang and Huang, 2001). The WUE of perennial ryegrass was determined to be 15 kg DM/ha/mm during dry summer periods in temperate pastures (Moot et al., 2008). Dry summer conditions could be similar to dry periods experienced more frequently with climate change. Another experiment evaluated seed production of perennial ryegrass under different irrigation levels, none, a single irrigation, and multiple irrigation events (Chastain et al., 2015). The WUE of perennial ryegrass was 5.82 kg/ha/mm with no irrigation, 5.30 kg/ha/mm with a single irrigation, and 4.78 kg/ha/mm with multiple irrigation events. Under dry conditions, perennial ryegrass was more efficient at using water, even though yields were reduced. Using modeling approaches to predict emergence, Tribouillois et al. (2018) found that annual ryegrass had the slowest rate of germination compared with 10 other cover crop species at 12 days to 80% germination. The authors also found that rainfall or irrigation after sowing and soil moisture at sowing for drilled cover crops were the first and second most important factors affecting germination, respectively. Finally, Curran et al. (2018) noted that all cover crop biomass, including annual ryegrass, was reduced by a 40-mm reduction in rainfall compared with the other trial years. This indicates the potential for biomass reductions if rainfall during the corn growing season is reduced.

Crimson clover is a winter annual clover species. Brar et al. (1991) found that germination remained at 80% or higher for temperatures between 10°C and 30°C; however, Ching (1975) found that only 20% of crimson clover seeds germinated at 30°C. With increasing summer temperatures, crimson clover germination may be inhibited due to climate change. An experiment including crimson clover found that climate change effects are buffered by microclimates such as low-lying areas. These microclimates might be habitable by crops and cover crops despite the effects of climate change. In this study, crimson clover was a warmer season crop and survived on the southern edge of the study range. With climate change, crimson clover will likely advance northward (Maclean et al., 2015). The WUE of other clovers was assessed by Moot et al. (2008) in temperate grasslands during dry summer months. The WUE was 40, 32, 33, and 30 kg DM/ha/mm for balansa clover, subterranean clover, white clover and Caucasian clover, respectively. Tribouillois et al. (2018) found that crimson clover emergence took eight days to 80% emergence under normal rainfall conditions compared with six days to 100% emergence under irrigated conditions. For interseeded crimson clover, it was noted by the USDA in 1913 that crimson clover emerged with light rainfall and perished with dry conditions afterwards (Westgate, 1913). This is important because after germination, cover crops need continued moisture to establish as plants. With climate change, it is expected that longer periods of drought may follow rainfall events, so this could impact the success of cover crops interseeded into corn.

Oilseed radish is a brassica cover crop that is sensitive to freezing temperatures. Sundermeier (2008) found that plants could not survive temperatures below -6°C. Germination of oilseed radish is optimized at 17.5°C daytime/2.5°C nighttime temperatures (Malik et al., 2010). With increasing temperatures due to climate change, oilseed radish germination may be reduced. A study from Saskatchewan, Canada found that when temperatures are greater than 30°C during flowering, yield loss occurs in oilseed rape (canola), a closely related brassica species. This occurred at the beginning of July in Canada (Kutcher et al., 2010). Radish growth in interseeded cover crops may be inhibited by high temperatures unless the maize creates an ideal microclimate. Pavlista et al. (2016) found that 30 cm of water produced the highest canola fresh weight, seed weight, and seed yield compared with 20 cm, 10 cm, and rainfed in Nebraska. Kang and Wan (2005) studied the WUE of *Raphanus sativus* under different soil water content ranging from -15 kPa to -55 kPa. WUE was highest under the lowest water potential and was 283 kg/ha/mm. Under the highest water potential, WUE was 179 kg/ha/mm. Yield was not reduced under different water potential levels. This indicates that under climate change with variable precipitation, radish may be resilient to dryer summer conditions. This is supported by Tribouillois et al. (2018) who found that *Brassica rapa* required 7 days to germinate under late summer conditions in France, which was the fastest of all of the species studied. The authors explained that *B. rapa* was resilient to late-summer water stress as it imbibes water and germinates quickly after a rainfall event.

Cover crops will be an important tool for climate change mitigation, but their growth and development will be affected by increasing temperatures and moisture variability. Higher summer temperatures may inhibit the germination of annual ryegrass, crimson clover, and oilseed radish late in the hot summer months such as July and August. Interseeding cover crops during May and June may provide a cooler time for improved germination of these species. Moisture is key to success in establishing cover crops. Modeling research points to a need to align cover crop seeding with rainfall events following seeding to improve cover crop germination and establishment (Constantin et al. 2015; Tribouillois et al. 2018).

Cover Crops Nitrogen Use

Annual ryegrass and cereal rye are cover crop species known for nitrogen scavenging (Clark, 2007). In an experiment in New York, annual ryegrass produced 2541 kg/ha of biomass and contained 29 kg/ha of N (1% N content). Kramberger et al. (2009) conducted research in Slovenia and determined the N content of annual ryegrass to be 1.1%. Mirsky et al. (2017) conducted an experiment using cereal rye and different N rates ranging from 0 to 180 kg/ha. Overall rye was able to take up about 50% of the N applied. In a maize interseeding experiment in Canada, cereal rye seeded at 101 kg/ha had a harvest N content of 3.1%, higher than that of annual ryegrass (Belfry and Van Eerd, 2016). Also, Vyn et al. (2000) found that cereal rye with biomass of 0.95 Mg/ha had N content of 20 kg/ha. Clover species are known for producing their own nitrogen through symbiotic relationships with *Rhizobia* bacteria (Clark, 2007). Belfry and Van Eerd (2016) found that crimson clover and red clover interseeded into maize had N contents of 2.8% and 3.7% with total N contents of 15.5 and 13.5 kg/ha, respectively. Den Hollander et al. (2007) also found that crimson clover had below 3% N content, while alsike, Persian, red and white clovers had N contents above 3%. Maximum biomass in this study for crimson clover was 634 g/m^2. Oilseed radish is also known for its ability to scavenge nitrogen (Clark, 2007). Belfry and Van Eerd (2016) found that oilseed radish accumulated 70 kg/ha of nitrogen and had a 4% N content. Vyn et al. (2000) found that oilseed radish had an N content of 19 kg/ha with a biomass of 1.4 Mg/ha.

Climate change could have different impacts on cover crops, especially in different regions. Peltonen-Sainio et al. (2009) pointed out that in a cooler climate, cover crops are likely to experience longer growing seasons and require increased nitrogen fertilizer. Crops included in this paper included cereals, pea, and oilseed radish. Basche et al. (2016) also point out that cereal rye in Iowa is expected to have increased biomass with climate change. This would also mean that there would be increased N requirements. On the other hand, reduced biomass and photosynthetic efficiency caused by heat stress, as seen with perennial ryegrass (Jiang and Huang, 2001), may result in the opposite effect of reduced nitrogen uptake due to reduced plant vitality. Fader et al. (2010) evaluated cereal production worldwide under climate change scenarios. Yields are expected to decline due to both increasing temperatures and decreased moisture in many parts of the world such as large parts of Africa. In other regions, such as central Europe, yields are expected to remain at high levels (Fader et al., 2010). Where yields are higher, it is likely that more N will be required to support larger biomass. Lower yielding regions will require less nitrogen. Beyond reduction in plant biomass, stress conditions such as heat and drought limit access to nutrients through limited root growth and low soil water content (Rathke et al., 2006). This experiment showed that applications of N alleviated drought stress because soil water was low, and plants could not access the N. Overall, the effects of climate change are likely to affect different regions differently in terms of cover crops and N use. Where cover crops are benefitted by climate change, N uptake might also be increased and vice versa.

6. Conclusion

Climate change in the Midwest is expected to bring higher temperatures and variability in precipitation patterns. Even with the beneficial effects on plant growth from increased CO_2 levels, high temperatures are expected to outweigh this effect and be detrimental to maize production as it will progress through developmental stages at a faster rate which decreases the time for biomass accumulation. Longer season hybrids will be important to continuing maize production, especially in areas where it is too warm too produce maize currently. Hybrids with greater WUE are also needed to manage the increased water stress expected with climate change. Improved management of water both in rainfed and irrigated systems will also be important moving ahead.

Cover crops will be affected by climate change but can also be used to mitigate its effects. High temperatures during July and August could limit germination and growth of annual ryegrass, crimson clover, and oilseed radish; seeding these crops earlier, such as in a maize interseeding system, or later in the season may improve their success. Cover crops will also prevent water loss from soils by reducing runoff, increasing infiltration, and decreasing deep drainage from the soil; therefore, cover crops can be used as one tool for water management for field crops such as maize. Cover crops also reduce greenhouse gas emission and reduce surface warming by increasing the albedo compared with a bare soil surface. Used with other improved management practices, cover crops will be important now and in the future with a changing climate.

Important Factors for Interseeding

Based on the previously presented information, Figure 1.02 was drawn to illustrate the various factors that influence interseeding of cover crops in corn. It is important to consider both the success of the cover crop in producing biomass and providing ecosystem services (including reducing soil erosion, controlling weeds, and cycling nutrients) and ensuring that the cover crop does not result in corn grain yield reduction. In my research, oilseed radish and annual ryegrass have had much greater establishment and biomass, overall, compared with crimson clover. This has been true for both single species and in the annual ryegrass – crimson clover – oilseed radish mixture. In terms of spring biomass, only annual ryegrass has overwintered despite the ability of crimson clover to sometimes overwinter.

Cover Crop Seeding Rate

Review of the interseeding literature showed little evidence that cover crop seeding rate affected the success of interseeding. However, seeding rate is still important when considering services provided by cover crops. Cover crop seeding rate in mixtures is especially important as grasses often dominate mixtures when seeded at too high of rates. Murrell et al. (2017) recommends seeding grasses at lower rates when in mixtures, and also seeding early enough for clovers and brassicas to establish, such as in late summer.

Cover Crop Optimal Temperature

The optimal temperature for cover crops is of some importance. One source found that germination of red clover was inhibited by high temperatures. This could be of greater importance with climate change, especially in an early interseeded system, where, without rain, seeds may lie on the soil surface in high temperatures until moisture is available for germination. For cold temperatures, germination of species can be inhibited as well as the overwintering potential of cover crops to maximize their benefits.

Interseeding Timing

Interseeding research has shown little evidence of corn grain yield loss from interseeding timing except for yield loss by crimson clover seeded 10 days after planting in one study. Studies that note a yield loss either do not mention weeds or state that weed control is an issue at that timing. Interseeding timing can affect establishment of cover crops and their ability to survive the summer under a corn canopy.

Light and Shade Tolerance

This factor is potentially the most important because the cover crops must be able to survive the period when the corn canopy closes in the summer. Both oilseed radish and crimson clover responded to shading in the literature by increasing leaf area in an attempt to capture more sunlight; crimson clover also increased petiole length. Annual ryegrass was also noted as a shade-tolerant species in the literature.

Cover Crop Species

Cover crop species selection is very important. Some crops are more or less shade tolerant, produce more biomass, or can tolerate different herbicides. Winter hardy species may be more useful in broadcast interseeded systems. Noland et al. (2018) found that fall biomass was greatly reduced in broadcast compared with drilled seedings; however, there were few differences in spring biomass for species that were able to survive the winter.

Herbicides Used for Weed Control

Control of weeds is of utmost importance. Cover crops must also be able to tolerate any residual herbicides to be successful. Reductions in corn grain yield in interseeding systems were generally due to poor weed control.

Rainfall Prior to Interseeding

In Tribouillois et al. (2018), soil moisture at the time of sowing was the second most important factor for successful establishment, and soil water potential was important for predicting emergence of drilled seeds. Broadcast seeds do not have the same seed to soil contact (Noland et al., 2018), so soil water content at the time of seeding may influence soil surface water availability to seeds.

Rainfall Following Interseeding

This factor was listed in multiple studies as being extremely important for the establishment of broadcasted cover crops, potentially as a means to create seed to soil contact for imbibition and germination.

Cover Crop Relative Growth Rate

This could be an important factor because cover crops need to get a quick start in order to survive the summer, and species establishment in a mixture may be impeded in RGR is low. However, cover crops that grow too quickly have the potential to compete with corn and produce seed that could lead to weed management issues. Annual ryegrass and oilseed radish have higher RGRs compared with crimson clover as reported in the literature. Crimson clover may not produce enough biomass early before the corn canopy closes and much of the light source is removed. This could partially explain crimson clover's lack of success in our interseeding trials to date.

Cover Crop Biomass Production

Interseeded cover crops do not reduce corn grain yield. Biomass production is critical to gain ecosystem services from cover crops.

Cover Crop Time to Emergence

Time to emergence is important because the cover crop must emerge prior to the shade of the corn canopy inhibiting emergence or growth. Cover crop germination occurs when water is available. Slowly emerging species might be susceptible to predation or decay. Annual ryegrass, crimson clover, and oilseed radish were all quick to emerge when conditions were suitable (i.e. moisture).

Conclusions

Interseeding cover crops into corn at the early vegetative stages could provide greater species options to producers in a grain corn rotation; selecting the right species or mixture of species to be successful in this system is of great importance. In my interseeding research, annual ryegrass and oilseed radish generally have greater emergence and fall density and biomass compared with crimson clover. Annual ryegrass and oilseed radish have higher RGRs compared with crimson clover which may be key to their success in this system. Cover crops must be able to emerge quickly, which all three species are capable of, and accumulate biomass quickly in order to survive the summer under the corn canopy. Despite clover's shade response of increased leaf area and increased petiole length, its minimal biomass may be too detrimental for survival in our system. Crimson clover was also noted as being susceptible to germination with early rainfalls in the spring then senescing with dry conditions following. This might also be extremely important regarding the survival of crimson clover in an interseeded system. More information is needed on the amount of rainfall required for germination and the frequency and amount of rainfall following germination for survival and growth for each species under shaded and non-shaded conditions. Lastly, the broadcast interseeding system used in my research, while a faster method, leads to a less consistent stand and greater reliance on rainfall compared with moisture already in the soil (Noland et al., 2018). Timing of interseeding prior to forecasted rainfall is essential to achieving cover crop emergence in interseeded cropping systems.

APPENDIX

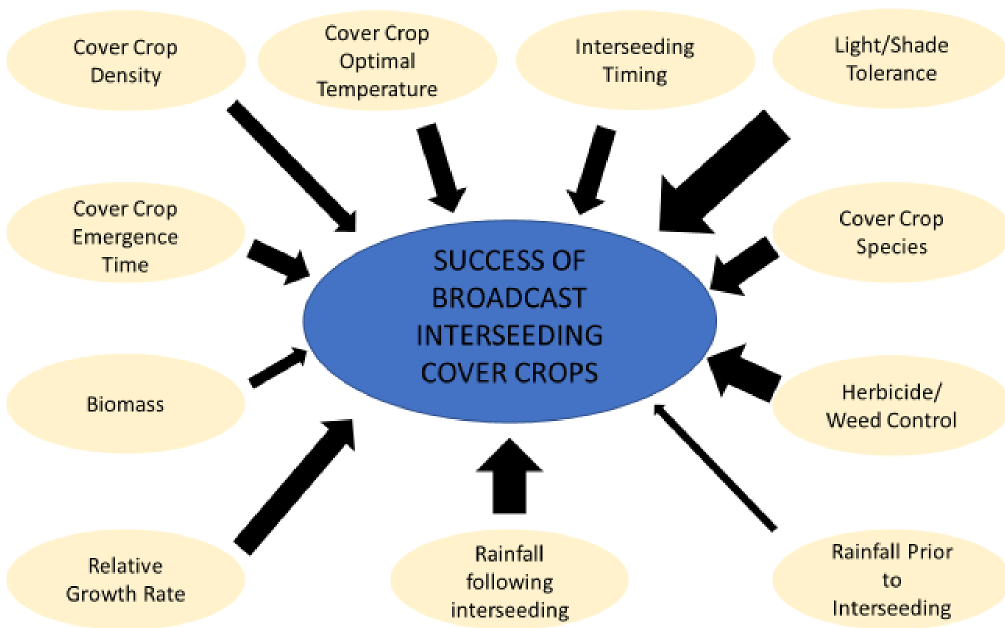
APPENDIX A

CHAPTER 1 FIGURES

Figure 1.01. Clover species, biomass production, and relative growth rate (RGR) (Den Hollander, 2007).

Species	**Biomass (kg/ha)**	**RGR (g/g/day)**
Alsike Clover	7740	0.082
Berseem Clover	5350	0.114
Crimson Clover	6340	0.092
Persian Clover	4265	0.152

Figure 1.02. Factors affecting the success of broadcast interseeding cover crops at the early vegetative corn growth stages. Wider arrows indicate that a factor is more important to the success of interseeding. Narrow arrows indicate a factor of less importance to interseeding or that the importance is not understood. See comments below for each factor.



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CHAPTER 2

INTERSEEDING COVER CROPS IN CORN

Abstract

Farmers benefit from the ecosystem services that cover crops provide, but time constraints limit the opportunity to seed cover crops following corn (*Zea mays* L.) harvest in the upper Midwest. Interseeding cover crops in corn during the early vegetative growth stages lengthens the cover crop growing season; however, cover crops may have difficulty establishing in standing corn, or conversely, compete with corn and reduce yield. The objectives of this research were to determine cover crop establishment when broadcast interseeded in corn from the V2-V7 growth stages, suppression of weeds by cover crops, and the effect of cover crops on corn grain yield. Annual ryegrass (*Lolium multiflorum* Lam.), crimson clover (*Trifolium incarnatum* L.), oilseed radish (*Raphanus sativus* L.), and a three-species mixture were interseeded in four site-years in Michigan. Annual ryegrass density was highest compared with oilseed radish and crimson clover 30 days after interseeding (DAI) and at harvest in October. Cover crop density was highest at the V4-V7 interseeding timings. Annual ryegrass produced more fall biomass (186 kg ha^{-1}) compared with crimson clover (112 kg ha^{-1}), and fall biomass was greatest at the V2, V3, and V5 interseeding timings. Spring biomass was 384 and 180 kg ha^{-1} for annual ryegrass and the cover crop mixture, respectively; these treatments reduced winter annual weed biomass. Corn grain yield was unaffected by cover crops at any interseeding timing. Crimson clover did not establish well in this experiment. Annual ryegrass and oilseed radish establish in V2-V7 corn without reducing corn grain yield.

Introduction

Diversifying crops in rotation improves productivity through enhanced soil biodiversity, nutrient availability, resource use efficiency, and increased soil organic matter (Tiemann et al., 2015; McDaniel et al., 2014). The addition of cover crops increases the diversity of corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) rotations that are common in Michigan and other Midwestern states. A farmer survey reported yield increases of 1.9 and 2.8% in corn and soybean, respectively, following the use of cover crops (CTIC, 2017). Improved soil quality (Clark, 2007), pest suppression (Stivers-Young, 1998; Wang et al., 2008; Isik et al., 2009; O'Reilly et al., 2011), and biological N fixation (Dabney et al., 2010) are some of the ecosystem services cover crops may provide.

The 2012 USDA Census of Agriculture reported that 2% of hectares in the United States were cover cropped (USDA-NASS, 2014) with a 60% increase in cover cropping since 2014 (CTIC, 2017). Current limitations to cover crop adoption are numerous, but seeding cost and return on investment, as well as a lack of breeding efforts and variety enhancement, were common responses from a recent farmer survey conducted throughout the U.S.; additionally, poor cover crop establishment was the most common factor limiting cover crop performance (Wayman et al., 2017). Furthermore, cover crop use tends to be lower in the northern Midwestern United States likely due to the shorter growing season to establish a cover crop. Winter cereals are the only option for seeding a cover crop in northern climates following corn harvest; however, establishment is still somewhat limited by the length of the growing season (Baker and Griffis, 2009). Another option for adding cover crops in corn monocultures or corn-soybean rotations is to interseed cover crops into corn prior to harvest (CTIC, 2017).

Interseeding cover crops is not a new practice. For example, in 1913, the USDA recommended interseeding crimson clover into corn, citing corn yield increases after many years of this practice (Westgate, 1913). The recent desire of farmers to integrate more cover crops into continuous corn or corn-soybean rotations has increased grower interest in interseeding cover crops. Currently, grasses are the most popular interseeded species, followed by clovers, and then Brassica species (CTIC, 2017). Researchers have examined interseeding several cover crop species including annual ryegrass (*Lolium multiflorum* Lam.) and crimson clover (*Trifolium incarnatum* L.) seeded as a single species and in mixtures (Abdin et al., 1998; Abdin et al., 1997; Belfry and Van Eerd, 2016; Caswell et al., 2019; Curran et al., 2018; Grabber et al., 2014; Scott et al., 1987; Youngerman et al., 2018; Zhou et al., 2000), and oilseed radish (*Raphanus sativus* L.) interseeded as a single species in Pennsylvania, USA and Ontario, Canada (Belfry and Van Eerd, 2016; Roth et al., 2015) and in a mixture in Minnesota (Noland et al., 2018)

A major concern with interseeding is whether cover crops will act as weeds and compete with corn (Hall et al. 1992). The competitiveness of weeds in corn depends on the time the weeds emerge in relation to corn emergence, the weed species, and the weed density. Weeds were not competitive with corn when weeds emerged after the V2 (Strahan, 2000), V4 (Travlos, 2011), and V5 (Harrison 2001) corn stages. These results suggest that cover crops could be interseeded in corn as early as the V2 corn growth stage without reducing corn grain yield, but competitiveness of cover crops, similar to weeds, may be dependent on species and density. In one study, yield losses occurred when cover crops were drill interseeded at the V2 corn growth stage in Pennsylvania (Curran et al., 2018). However, Baributsa et al. (2008) reported no adverse effects when red clover was interseeded in corn in late May and early June. Furthermore, Noland et al. (2018) reported no reduction in corn yield when cover crops were interseeded at the V7 corn growth stage, regardless of interseeding method (drilled, broadcast, broadcast + incorporation). There is no research that directly compares interseeding success at each of the V2-V7 corn stages. Additionally, most interseeding research has evaluated drilled interseeding; however, we broadcast interseeded in this research, as farmers are interested in a faster method for interseeding. The objectives of this research were to: 1) evaluate cover crop establishment, growth and biomass production when interseeded in corn at the V2 – V7 growth stages, 2) determine if cover crops provide weed suppression, and 3) determine if broadcast interseeded cover crops reduce corn grain yield.

Materials and Methods

Field experiments were conducted in 2015-2016, 2016-2017, and 2017-2018 at the Michigan State University Agronomy Farm (MSUAF) in East Lansing, MI (42°42'38.64" N, 84°28'16.65" W) and in 2017-2018 at the Saginaw Valley Research and Extension Center (SVREC) in Richville, MI (42°17'59.45" N, 83°41'51.47" W). The soil type at MSUAF in 2015-2016 and 2017-2018 was an Aubbeenaubbee-Capac sandy loam (fine-loamy, mixed, active, mesic aeric epiaqualfs; fine-loamy, mixed, active, mesic aquic glossudalfs) and in 2016-2017, a Conover loam (fine-loamy, mixed, active, mesic aquic hapludalfs). The soil type at SVREC was a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic typic epiaquolls; fine-loamy, mixed, semiactive, mesic aeric glossaqualfs). Soil organic matter ranged between 2.8-2.9%, and pH ranged from 5.8-7.6 at MSUAF sites. Soil organic matter was 3.0% and pH was 7.5 at SVREC. The experimental design was a split-plot with four replications; cover crop species was the main plot and interseeding timing the subplot. Subplot size was 3 m wide (4 corn rows) and 12 m long. Cover crop species included annual ryegrass, oilseed radish (var. Tillage

Radish®), and crimson clover with NitroCoat® seed coating, and a mixture of the three species (Center Seeds, Springport, MI). Interseeding rates were 18 kg ha^{-1} for annual ryegrass, 9 kg ha^{-1} for oilseed radish, 18 kg ha^{-1} of coated seed for crimson clover, and 11 kg ha^{-1}, 2 kg ha^{-1}, and 2 kg ha^{-1} of annual ryegrass, oilseed radish, and crimson clover, respectively, for the mixture. The mixture was commercially available as "PeakBlend Indy" (Center Seeds). Seeds per square meter for single species were 829, 75, and 355 for annual ryegrass, oilseed radish, and crimson clover, respectively. For the mixture, seeds per square meter were 507, 17, and 39 for annual ryegrass, oilseed radish, and crimson clover, respectively. Seeding rates were within the recommended seeding rates provided by the Sustainable Agriculture Research and Education publication, "Managing Cover Crops Profitably" (SARE; Clark, 2007). Interseeding timings were based on the corn growth stage measured by the leaf collar method (Abendroth et al., 2011) and included the V1 (MSUAF 2015 only), V2, V3, V4, V5, V6, and V7 (excluding MSUAF 2015) growth stages.

At each MSUAF site year, fields were chisel plowed in the fall prior to the experiment and soil finished in the spring using a Kongskilde Triple K soil finisher (Kongskilde Agriculture, Albertslund, Denmark) just prior to planting. Nitrogen as urea (CH_4N_2O) was broadcast prior to tillage and incorporated at a rate of 155 kg ha^{-1}. An additional 32 kg ha^{-1} of N as urea and ammonium nitrate (NH_4NO_3), P as P_2O_5, and K as K_2O were applied in a 5 x 5-cm band as starter at planting. At SVREC, tillage included a disc ripper in the fall prior to the experiment followed by a Kongskilde Triple K soil finisher in the spring prior to planting. Nitrogen as CH_4N_2O at 157 kg ha^{-1} was applied prior to planting. At each site year, glyphosate (N-(phosphonomethyl)glycine)-resistant corn was planted in late-April to mid-May using a four-row corn planter in 76-cm rows. Seeding depth was 3.8 cm at MSUAF and 5 cm at SVREC and the seeding rate in all site years was 79,000 seeds ha^{-1}.

Cover crops were broadcast interseeded at the V1-V7 corn growth stages using a hand-spreader between the first and fourth corn rows so that three interrow spaces were interseeded. Interseeding occurred from mid-May to late June and dates varied by site year depending on the corn planting date and corn development stage (Table 2.01). Glyphosate at 0.84 kg ae ha^{-1} was applied the day of each interseeding using a tractor-mounted, compressed air sprayer to control emerged weeds. A weed-free control plot was included to determine corn grain yield in the absence of weeds or cover crops; weeds were controlled using glyphosate applied prior to planting and at the V3 and V6 corn stages. A plot with no cover crops and no weed control (weedy) was also included. The most prevalent weed species were giant foxtail (*Setaria faberi*), annual bluegrass (*Poa annua*), common lambsquarters (*Chenopodium album*), common ragweed (*Ambrosia artemisiifolia*), Powell amaranth (*Amaranthus powellii*), and dandelion (*Taraxacum officionale*).

Two, 0.25 m^2 quadrats were permanently marked between the second and third corn rows. Cover crop density was measured 14 and 30 days after interseeding (DAI) in each quadrat. Fall cover crop density and aboveground cover crop biomass was harvested from the quadrats in October each year prior to corn harvest. For the cover crop mixture, individual species density was recorded, but biomass was not separated by species. Weed density was measured 30 DAI and prior to corn harvest in the same quadrats. Aboveground fall weed biomass was collected at the time of cover crop harvest but was not separated by species. In April of the following spring, cover crop and weed density and biomass were measured from two 0.25 m^2 quadrats placed adjacent to the previous quadrats between the second and third corn rows. Dry weights were recorded following oven drying at 80°C for at least three days.

Corn grain was harvested from the two center rows using a plot combine; the weight of the harvested grain was recorded and adjusted to 15% moisture content. In 2016 and 2017, ground level photosynthetically active radiation (PAR) was measured between the center two rows near the permanent quadrats in each plot at least four times from the first interseeding date to the time of corn pollination using a SunScan Canopy Analysis System type SS1 (Delta T Devices Ltd., 2016). Daily rainfall data was acquired from weather stations located at MSUAF and SVREC as part of the Michigan Enviro-weather Network (MAWN, 2018).

Statistical Analyses

We analyzed cover crop density and biomass, weed density and biomass, and corn grain yield using PROC MIXED in SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2012). Normality of data was checked by examining residual distribution. A Poisson distribution was considered for density data; however, the results did not differ compared with analyzing the data using a normal distribution. Data were initially analyzed by site year to determine if data could be combined over site years. Site years were run individually when F tests for site year were significant ($P \leq 0.05$). Cover crop species, interseeding timing, and the interaction of the two were considered fixed effects, and site year (when not significant), and replication nested within site year were considered random effects. Analyses were conducted to determine differences in cover crop density, cover crop biomass, weed density, weed biomass, and corn grain yield. In 2015, both shoot and root biomass were collected, and shoot biomass was not separated, so those data are not included. Comparisons of least square means at $P \leq 0.05$ were made if F tests were significant ($P \leq 0.05$) using *t* tests conducted by the SAS pdmix800 macro (Saxton, 1998). Reported treatment means were significantly different when the *P*-value was ≤ 0.05, unless otherwise noted.

Results and Discussion

Precipitation and PAR

Precipitation near the time of interseeding varied greatly between site years; cumulative rainfall from May 1st to July 15th totaled 30, 12, 15, and 18 cm for MSUAF 2015, MSUAF 2016, MSUAF 2017, and SVREC 2017, respectively (Figure 2.01A-D). This resulted in differences in cover crop density and biomass production. We measured photosynthetically active radiation until corn reached the reproductive tasseling stage, which occurred within the first two weeks of July each year; at that time, PAR was reduced by 80% in each site year (data not shown). Previous research has shown that decreased PAR reaching cover crops in an interseeded system reduced biomass production (Youngerman et al., 2018).

Cover Crop Density

Annual ryegrass had the highest plant density 30 DAI compared with crimson clover and oilseed radish (Table 2.02). By harvest, annual ryegrass density was highest at 120 plants m^{-2} compared with crimson clover and oilseed radish which had 32 and 8 plants m^{-2}, respectively. As a percent of the seeded rate, annual ryegrass and oilseed radish both had 12% establishment, whereas crimson clover only had 7% establishment. Cover crop density 30 DAI was highest at the V5, V6, and V7 interseeding timings at 84, 72, and 80 plants m^{-2}, respectively, compared with the V2 and V3 interseeding timings (Table 2.02). When measured at harvest, density was highest at the V7 interseeding timing at 76 plants m^{-2} compared with all other interseeding timings. The interseeding timing results were largely driven by annual ryegrass in the interaction between cover crop species and interseeding timing (Table 2.03). Crimson clover density 30 DAI and at harvest was highest at the V5 and V7 timings, and there was no difference in oilseed radish density when compared across interseeding timings (Table 2.03). Cover crop density at harvest was usually reduced compared with the 30 DAI measurements indicating some attrition of plants throughout the season. The cover crop mixture was dominated by annual ryegrass at 20 plants m^{-2}; only 1 plant m^{-2} for oilseed radish and crimson clover established in the mixture (data not shown). Other research has shown that annual ryegrass can overwhelm other species in a mixture when seeded at too high of a rate proportionally (Kramberger et al., 2014).

The data suggests that rainfall following interseeding often improved cover crop establishment (Figure 2.01). Precipitation from May 1 to July 15 was highest for MSUAF 2015 (24 cm) and lowest for MSUAF 2016 (3.7 cm). Cover crop density was generally higher for MSUAF 2015 indicating that consistent rainfall improved emergence and survivability of cover crops in 2015. At the MSUAF 2016 site year, rainfall greater than 2.5 cm following the V7 interseeding resulted in greater emergence; however, at the MSUAF 2017 site year, a similar amount of precipitation followed the V6 and V7 interseeding timings but did not increase emergence. Other researchers have shown that rainfall following interseeding is crucial for cover crop establishment (Tribouillois et al., 2018; Constantin, 2015; Wilson et al., 2014; Collins and Fowler, 1992). In previous research, annual ryegrass seedlings were more tolerant of dry conditions following germination compared with a mustard and a vetch species (Constantin, 2015). In our research, annual ryegrass seedlings survived the two weeks without precipitation whereas crimson clover did not.

Other studies support our observations that poor establishment of crimson clover was likely caused by a lack of precipitation (Cooper at al., 1987), fatal germination when a significant rainfall event triggered germination and then a dry period followed (Constantin et al., 2015) or the 80% reduction in PAR beneath the corn canopy (data not shown; Van Sambeek, 2007). However, crimson clover establishment was greater at later compared with earlier interseeding times, suggesting the lack of sunlight was probably not the reason for poor emergence in the early interseeded treatments.

Cover Crop and Weed Biomass

Averaged over interseeding timings, annual ryegrass and the annual ryegrass mixture produced 186 and 155 kg ha^{-1}, respectively, of fall biomass (Table 2.04). Biomass of annual ryegrass was greater than crimson clover and was not different from oilseed radish biomass (Table 2.04; Figure 2.02A and B). By the following spring, annual ryegrass biomass had doubled, whereas biomass of the mixture increased by only 14%. Oilseed radish is not tolerant of winter temperatures below 6°C (Sundermeier, 2008) and did not overwinter in this experiment; crimson clover did not always overwinter and produced only 8 kg ha^{-1} of biomass in the spring. Cover crops interseeded early accumulated more biomass prior to canopy closure compared with later interseeding timings. This was likely due to the length of time from interseeding to canopy closure. Fall biomass, when combined across cover crop species, was greatest at the V2, V3, and V5 interseeding timings, and lowest at the V6 and V7 interseeding timings (Table 2.04). For spring biomass, there was no difference in biomass of annual ryegrass or the annual ryegrass mixture across interseeding timings. Annual ryegrass was able to produce the same amount of spring biomass, regardless of interseeding timing probably due to biomass accumulation following corn harvest and in the early spring.

The weedy control treatment had the greatest fall weed biomass compared with all cover crop treatments (Table 2.04). Fall weed biomass, when combined across cover crop species, was greatest at the V2 interseeding timing; V3 weed biomass was also greater than the V5-V7 interseeding timings (Table 2.04). Differences in weed biomass were probably a result of the time of peak weed emergence as it related to the time of interseeding. More summer annual weeds emerged following glyphosate application at the V2 and V3 interseeding timings compared with the later applications of glyphosate prior to later interseedings.

Winter annual weed suppression was highest where annual ryegrass overwintered (Table 2.04). Crimson clover produced only 8 kg ha^{-1} of spring biomass that was not sufficient to suppress winter annual weeds. The spring weed biomass in the crimson clover treatments was not different from the biomass in the weedy and weed-free controls (data not shown), indicating that it did not effectively suppress weeds. Previous researchers have documented weed suppression from annual ryegrass and oilseed radish (O'Reilly et al., 2011; Isik, 2009; Wang et al., 2008; Stivers-Young, 1998).

Corn Grain Yield

A windstorm at SVREC 2017 one day prior to harvest caused severe lodging, so yield was not included for that site year. Weeds reduced corn yield in the weedy control plots at MSUAF 2015 and 2017 (Table 2.05). Drought during the growing season at the MSUAF 2016 site resulted in low grain yields, and no difference in corn yield across all treatments. Corn grain yield did not differ from the weed- and cover crop-free control when cover crops were interseeded at V2 or later timings (Table 2.05). When the V1 interseeding timing was included in the analysis of the MSUAF 2015 site year, corn grain yield was reduced in this treatment. Fall weed biomass at the V1 interseeding timing was at least four times greater than at any other interseeding timing (data not shown).

Conclusions

Annual ryegrass and oilseed radish established when broadcast interseeded in corn from the V2-V7 corn growth stages in Michigan; however, crimson clover emergence was low as a percentage of the seeding rate. Interseeded cover crops are at risk of attrition from lack of light and rain reaching the soil surface in a standing corn crop, especially as corn populations increase (Youngerman et al., 2018). Though cover crop density was greatest with later interseeding timings, maximum fall biomass occurred when cover crops were interseeded early. By spring, however, annual ryegrass biomass was similar for all interseeding timings, suggesting that farmers have a large 'window' for interseeding annual ryegrass in grain corn and maximizing biomass. Early interseeding timings may be optimal for oilseed radish, as this species winterkills. We measured fall biomass at the time of corn harvest, and oilseed radish continued to accumulate biomass until the first hard frost in mid- to late-November (data not collected). It would be of interest to determine if the differences in radish interseeding biomass diminished by late November.

It was evident that cover crops were not competitive with corn or summer annual weeds at the densities established at our research sites. Our research used broadcast interseeders, which results in lower densities of cover crops compared with drilled interseeders (Noland et al., 2018). Further research is necessary to explore the competitiveness of higher densities of cover crops seeded from V2 -V5 in corn, since annual ryegrass drill interseeded prior to V4 produced over 1500 kg ha^{-1}, nine times greater than average biomass production in our research, and reduced corn grain yield (Curran et al., 2018). Differences in cover crop biomass production may also result from differences in growing conditions. Further research should could include seeding ratios of mixtures and include more diverse cover crop mixtures, as well as integrated weed management strategies to control weeds in early cover crop interseeding in corn. The potential benefit to soil health and nutrient cycling from interseeding cover crops in corn monocultures and corn-soybean rotations requires further research.

APPENDIX

APPENDIX B

CHAPTER 2 TABLES AND FIGURES

Table 2.01. Cover crop interseeding dates and corn harvest dates for MSUAF[a] 2015, 2016, and 2017, and SVREC[b] 2017.

Interseeding Timing	MSUAF 2015	MSUAF 2016	MSUAF 2017	SVREC 2017
	Seeding Date			
V1	13 May	-	-	-
V2	21 May	31 May	2 June	23 May
V3	28 May	3 June	6 June	26 May
V4	3 June	7 June	13 June	2 June
V5	8 June	10 June	16 June	8 June
V6	15 June	15 June	23 June	12 June
V7	-	22 June	28 June	19 June
Corn Harvest	18 Oct.	24 Oct.	13 Oct.	12 Oct.

[a] Michigan State University Agronomy Farm, East Lansing, MI.
[b] Saginaw Valley Research and Extension Center, Richville, MI.

Table 2.02. Cover crop emergence by the main effect of species and interseeding timing, combined over site years, at 30 days after interseeding (DAI) and just prior to corn harvest.

Cover Crop	30 DAI	Harvest
	plants m^{-2}	
annual ryegrass	144 a[a]	120 a
crimson clover	40 b	32 b
oilseed radish	12 b	8 b
±SEM[b]	(± 20)	(± 12)
P-value	<0.0001	0.0002
Interseeding Timing	**30 DAI**	**Harvest**
	plants m^{-2}	
V2	40 c[a]	44 b
V3	52 bc	44 b
V4	68 ab	52 b
V5	84 a	52 b
V6	72 a	56 b
V7	80 a	76 a
±SEM[b]	(± 20)	(± 9)
P-value	0.0003	0.0101

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b] Standard error of mean for LSD comparisons.

Table 2.03. Cover crop emergence separated by species at each interseeding timing, combined over site years at 30 days after interseeding (DAI) and just prior to corn harvest.

	30 DAI			Harvest		
Interseeding Timing	annual ryegrass	crimson clover	oilseed radish	annual ryegrass	crimson clover	oilseed radish
			plants m^{-2}			
V2	88 c[a]	24 c	12 a	96 b	28 bc	8 a
V3	108 bc	36 c	8 a	100 b	24 c	8 a
V4	152 ab	40 bc	12 a	112 b	36 abc	12 a
V5	180 a	56 a	16 a	116 b	44 ab	12 a
V6	180 a	28 c	8 a	124 b	24 c	8 a
V7	176 a	52 ab	20 a	174 a	44 a	12 a
±SEM[b]	(± 51)	(± 9)	(± 4)	(± 26)	(± 11)	(± 3)
P-value	0.0036	0.0004	0.0625	0.0295	0.0115	0.2483

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 2.04. Cover crop and weed biomass measured in the fall of interseeding and the spring following interseeding for the main effects of cover crop species and interseeding timing.

	Fall		Spring	
Cover Crop Treatment	Cover Crop	Weed	Cover Crop	Weed
	Biomass kg ha^{-1}			
annual ryegrass	186 a[b]	249 a	384 a	138 c
crimson clover	112 b	227 a	8 c	381 a
oilseed radish	147 ab	246 a	0 c	299 ab
mixture	155 ab	210 a	180 b	215 bc
±SEM[c]	(± 24)	(± 64)	(± 40)	(± 142)
P-value	0.0337	0.8633	<0.0001	<0.0001
Interseeding Timing				
	Biomass kg ha^{-1}			
V2	222 a[b]	497 a	142 a	224 a
V3	183 ab	286 b	240 a	224 a
V4	138 bc	218 bc	169 a	303 a
V5	174 ab	152 c	190 a	284 a
V6	87 c	110 c	188 a	306 a
V7	98 c	134 c	217 a	206 a
±SEM[c]	(± 27)	(± 69)	(± 43)	(± 144)
P-value	<0.0001	<0.0001	0.2362	0.3038
weedy[a]	-	1509*	-	185
weed-free[a]	-	124	-	281

[a] Analyzed separately and compared with each cover crop by interseeding timing combination;
[b] Within columns, means with the same letter are not significantly different at α = 0.05 according to Fisher's LSD.
[c] Standard error of mean for LSD comparisons.
* Values with an asterisk are significantly different at α = 0.05 according to Fisher's LSD.

Table 2.05. Corn grain yield at each site year[a] for the main effects of cover crop species and interseeding timing.

	Corn Grain Yield		
Cover Crop Treatment	MSUAF 2015	MSUAF 2016	MSUAF 2017
		Yield Mg ha^{-1}	
annual ryegrass	12.4 a[c]	12.1 a	10.6 a
crimson clover	12.7 a	12.4 a	10.6 a
oilseed radish	12.6 a	12.4 a	10.5 a
mixture	12.4 a	12.4 a	10.4 a
±SEM[d]	(± 0.4)	(± 0.3)	(± 0.6)
P-value	0.7473	0.8146	0.8774
Interseeding Timing			
		Yield Mg ha^{-1}	
V1	10.2 b[c]	-	-
V2	12.8 a	12.7 a	10.4 a
V3	12.7 a	12.4 a	10.6 a
V4	13.2 a	12.1 a	10.0 a
V5	13.3 a	12.3 a	11.0 a
V6	12.9 a	12.5 a	10.7 a
V7	-	11.9 a	10.4 a
±SEM[d]	(± 0.4)	(± 0.3)	(± 0.6)
P-value	<0.0001	0.5005	0.1534
weedy[b]	10.3*	12.4	7.6*
weed-free[b]	12.9	12.6	10.0

[a] SVREC 2017 was not included due to severe lodging caused by a wind storm.
[b] Analyzed separately and compared with each cover crop by interseeding timing combination;
[c] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[d] Standard error of mean for LSD comparisons.
* Values with an asterisk are significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Figure 2.01. Cover crop emergence as a percent of the seeding rate measured 30 days after interseeding (DAI) (black bars) and just prior to corn harvest in the fall (gold bars). Each pair of bars indicates the date of interseeding from V1-V6 for MSUAF 2015 (A), and from V2-V7 for MSUAF 2016 (B), MSUAF 2017 (C), and SVREC 2017 (D). Cumulative precipitation from May 1st to July 15th during the interseeding period is indicated by the red line.

MSUAF 2015

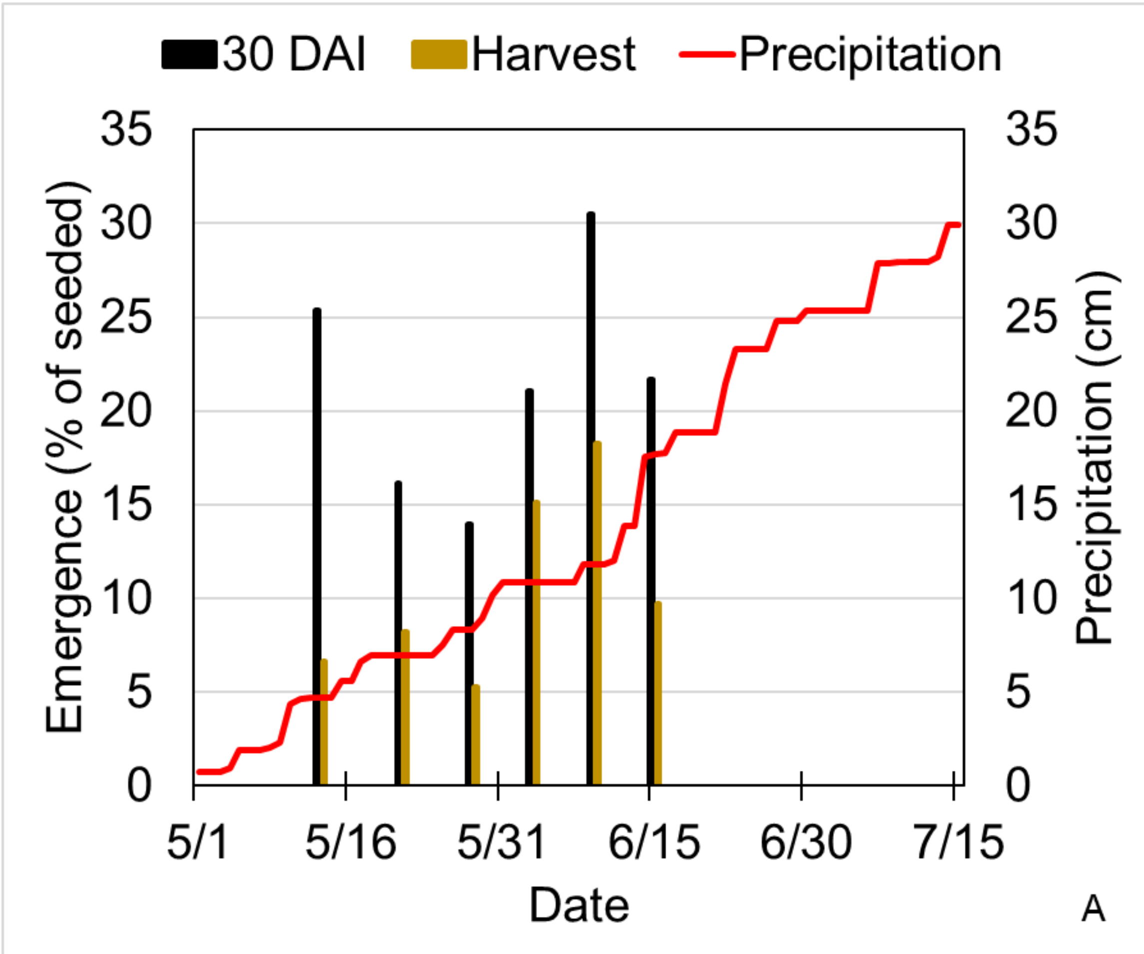

Figure 2.01 (cont'd)
MSUAF 2016

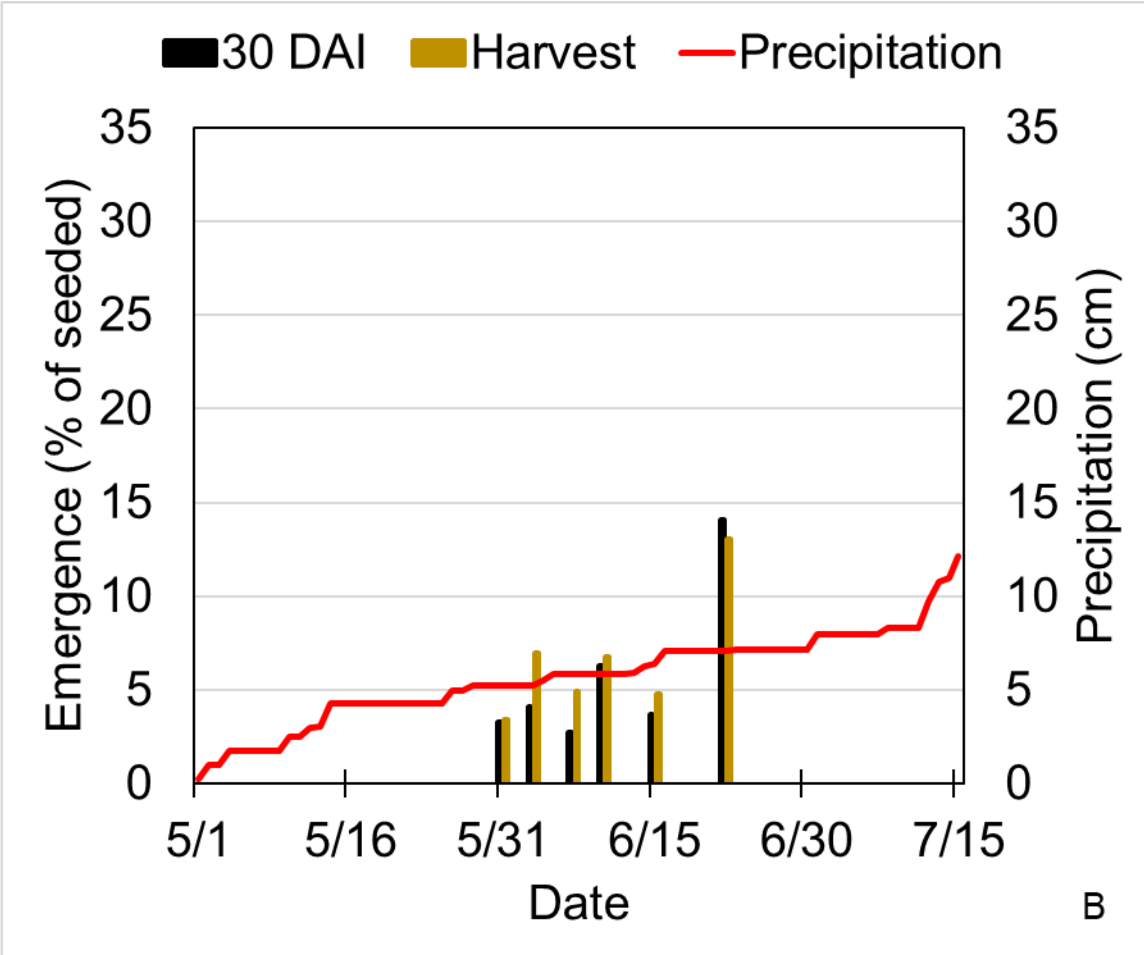

Figure 2.01 (cont'd)
MSUAF 2017

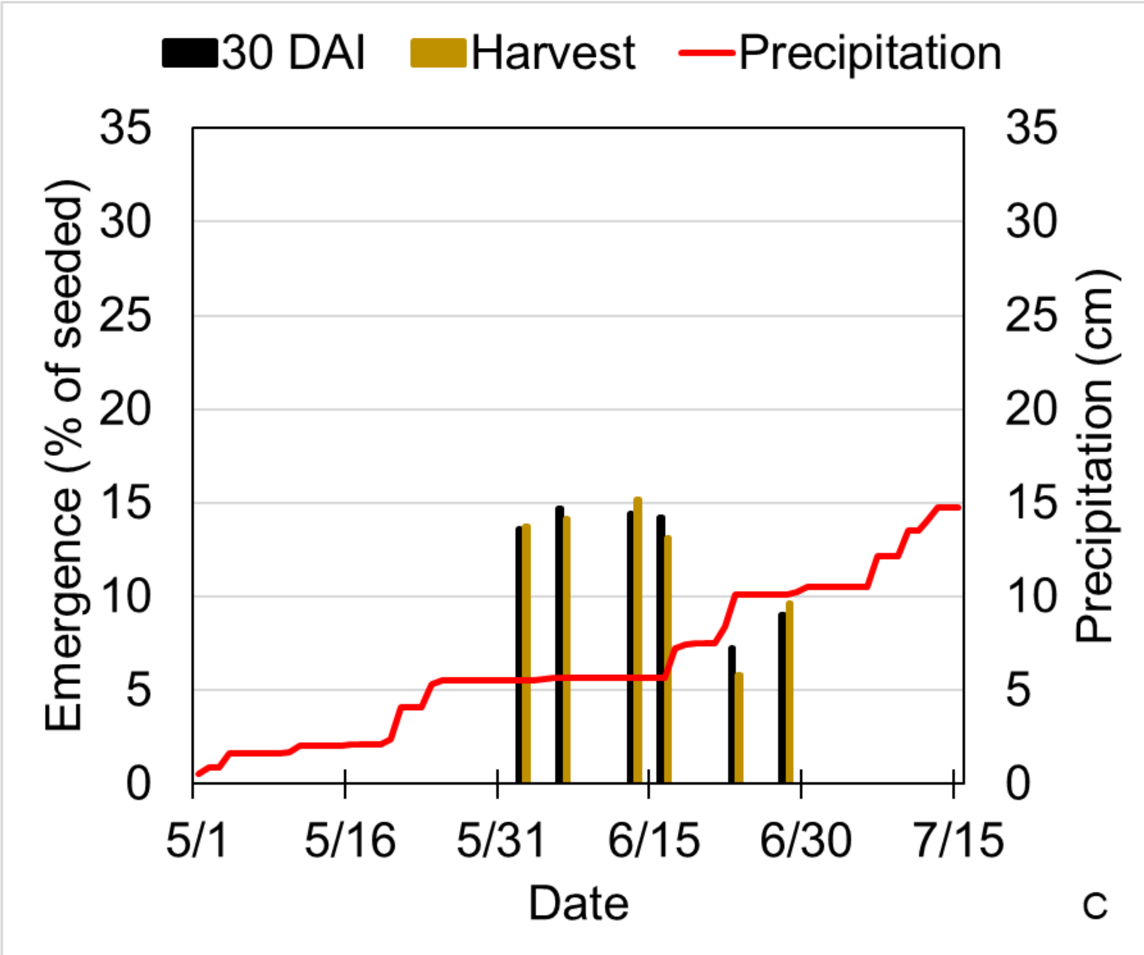

Figure 2.01 (cont'd)
SVREC 2017

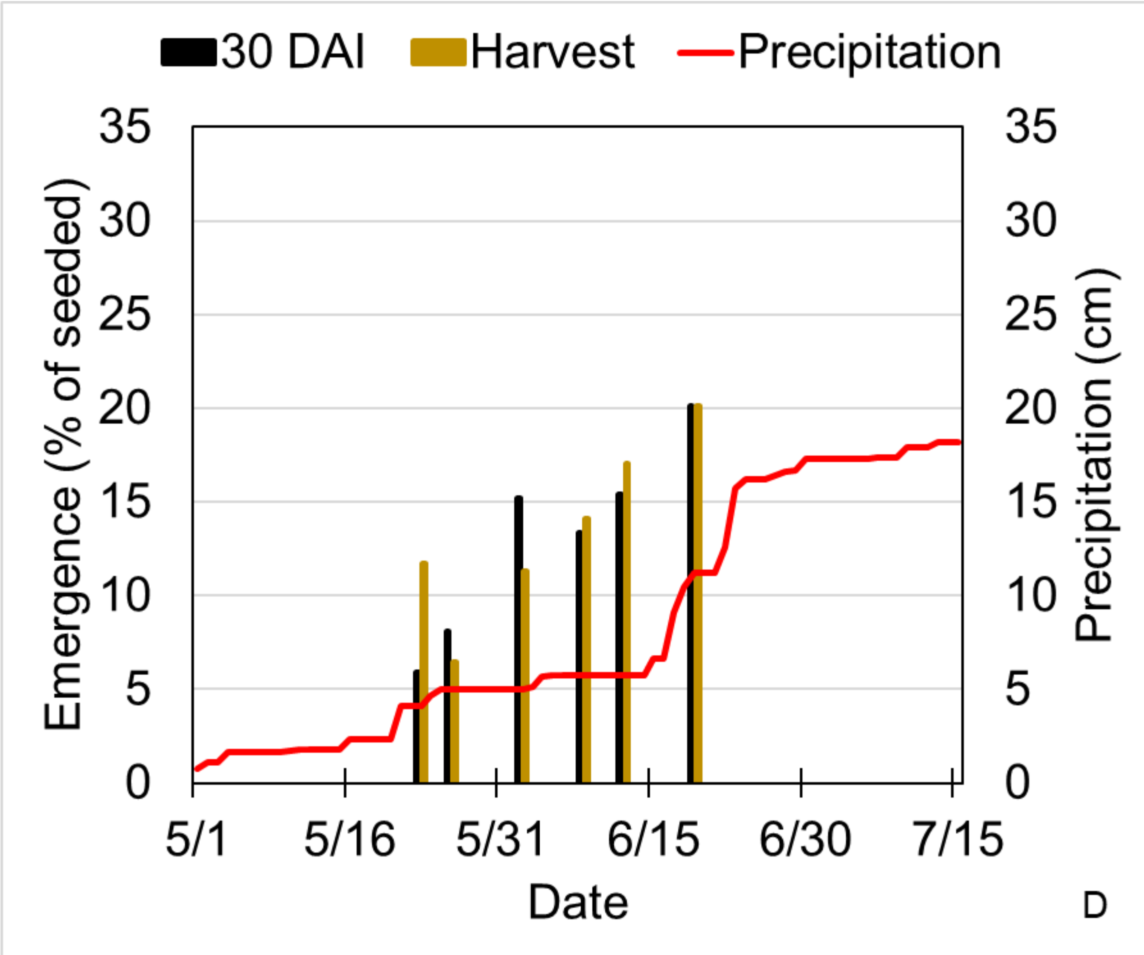

Figure 2.02. Photos of fall cover crop biomass from 2015 when rainfall was sufficient for establishment of oilseed radish (A) and annual ryegrass (B).

Oilseed radish

Figure 2.02 (cont'd)
Annual Ryegrass

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CHAPTER 3

INTERSEEDED ANNUAL RYEGRASS, OILSEED RADISH, AND CRIMSON CLOVER TOLERANCE TO RESIDUAL HERBICIDES COMMONLY USED IN CORN

Abstract

Cover cropping is limited following corn harvest in the Upper Midwest of the United States due to seasonal constraints. Grass, clover, and brassica cover crops can be interseeded into corn; however, this is problematic for weed control as cover crops must be tolerant of herbicides applied to manage weeds. The objective of this research was to determine the tolerance of broadcast interseeded annual ryegrass, oilseed radish, and crimson clover to PRE and POST residual herbicides in corn. From 2016 to 2018 field trials were conducted in Michigan to determine the tolerance of annual ryegrass, oilseed radish, and crimson clover to 13 PRE and 14 POST (applied at V2 corn) herbicides. Cover crops were interseeded into corn at the V3 and V6 stages. Greenhouse experiments evaluating these species were also conducted from 2016 to 2018; PRE and POST herbicides were applied at 1x, 0.5x, and 0.25x (0.25x was PRE only) field application rates. Annual ryegrass can be interseeded at V3 or V6 following PRE applications of atrazine, clopyralid, saflufenacil, bicyclopyrone, isoxaflutole, and mesotrione, and POST applications of atrazine, bromoxynil, and mesotrione. Oilseed radish can be interseeded at V3 or V6 following PRE applications of clopyralid, atrazine, S-metolachlor, bicyclopyrone, and isoxaflutole and following applications of acetochlor, dimethenamid-P, or mesotrione at V6. Oilseed radish can also be interseeded following POST applications of atrazine (571 g ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, and dimethenamid-P + topramezone. In greenhouse trials, crimson clover was tolerant to PRE applications of

rimsulfuron, saflufenacil, and pyroxasulfone. Annual ryegrass and oilseed radish can be interseeded at the V3 and V6 corn stages, but special attention must be given to cover crop species selection when following herbicide applications in corn.

Introduction

Diverse crop rotations improve crop productivity by enhancing soil health and resource use efficiency (Tiemann et al. 2015; McDaniel et al. 2014). Cover crops diversify crop rotations; however, only about 2% of agricultural hectares are seeded with cover crops (USDA-NASS 2019). Cover crops can increase diversity in corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.) rotations, but adding cover crops can be difficult. In the Upper Midwest United States, there is a limited amount of time to establish a cover crop following corn grain and soybean harvest in the fall. While winter cereals can be seeded following harvest, cover crop establishment and growth can be limited by the short growing season (Baker and Griffis 2009).

Interseeding cover crops in corn during the early vegetative growth stages provides farmers with an option to establish a cover crop in a grain corn rotation (CTIC 2017). Though not a new practice, a variety of cover crops have been interseeded, including but not limited to annual ryegrass (*Lolium perenne* L. spp. *multiflorum* (Lam.) Husnot), crimson clover (*Trifolium incarnatum* L.) (Curran et al. 2018; Belfry and Van Eerd 2016; Grabber et al. 2014; Zhou et al. 2000), and oilseed radish (*Raphanus sativus* L.) (Belfry and Van Eerd 2016; Roth et al. 2015). Farmers reported that grasses are currently the best cover crop choice for interseeding (51%), followed by clovers (14%) and radish (10%) (CTIC 2017).

In previous research, residual herbicides reduced cover crop establishment and growth when seeded in late summer or fall. In Arkansas, PRE applications of atrazine, fluridone, and pyrithiobac reduced biomass of fall-seeded crimson clover by 30, 30, and 33%, respectively, and atrazine and fluridone reduced biomass of fall-seeded rapeseed by 20 and 22%, respectively (Palhano et al. 2018). Imazethapyr injured oilseed radish seeded three months after herbicide application by up to 65% in Ontario, Canada (Yu et al. 2015). Pyroxasulfone consistently reduced fall-seeded annual ryegrass biomass by 67% in Missouri; other herbicides reduced establishment of crimson clover (Cornelius and Bradley 2017). In Pennsylvania, pyroxasulfone and S-metolachlor reduced biomass of annual ryegrass interseeded at V5 growth stage corn (Abendroth et al. 2011) by 80 and 86%, respectively, and red clover *(Trifolium pretense* L.) biomass was reduced by up to 98% by mesotrione (Wallace et al. 2017).

The body of research on cover crop tolerance to herbicides is limited to few cover crop species, soil types, and climatic regions, and very little research has been conducted for cover crops interseeded within zero to five weeks following a residual herbicide application. Currently, there is no peer reviewed information on the tolerance of cover crops interseeded following POST herbicide applications at V2 to V3 corn. Research is needed to support recommendations on cover crop seeding timing in relation to herbicide and application timing. The objectives of this research were to evaluate the effects of PRE and POST herbicides on annual ryegrass, crimson clover, and oilseed radish establishment when interseeded at V3 and V6 corn.

Materials and Methods

Field Experiments

PRE herbicide field experiments were conducted in 2016, 2017, and 2018 at the Michigan State University Agronomy Farm (MSUAF) in East Lansing, MI (42°42'38.64" N, 84°28'16.65" W), at an on-farm location located in Springport, MI (42°21’23.06” N, 84°41’20.25” W), and in 2018 only at the Saginaw Valley Research and Extension Center

(SVREC) in Richville, MI (42°17'59.45" N, 83°41'51.47" W) for a total of seven site-years (Table 1). POST herbicide field experiments were conducted in 2017 and 2018 at MSUAF and in 2018 in Springport and SVREC for a total of 4 site-years. Soils at MSUAF included a Conover loam (fine-loamy, mixed, active, mesic Aquic Hapludalfs) in 2016 and 2018 and a Riddles-Hillsdale sandy loam (fine-loamy, mixed, active, mesic Typic Hapludalfs; coarse-loamy, mixed, active, mesic Typic Hapludalfs) in 2017. Soils at SVREC were a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquolls; fine-loamy, mixed, semiactive, mesic Aeric Glossaqualfs). Soils at Springport were a Riddles sandy loam (fine-loamy, mixed, active, mesic Typic Hapludalfs) each year. At MSUAF, soil pH ranged from 5.6 to 6.2 and soil organic matter (SOM) ranged from 1.8 to 3.3. Soil pH was 7.5, and SOM was 3.0 at SVREC. Springport soil pH ranged from 5.9 to 6.2, and SOM ranged from 1.6 to 1.8. The experimental design for PRE and POST experiments was a strip-plot with four replications with cover crop species interseeded in strips at both V3 or V6 corn and herbicides applied in strips perpendicular to cover crop planting. Plot size was 9 m^2 (4, 0.76-m wide corn rows by 3-m wide herbicide application path).

Tillage at MSUAF included chisel plowing to a 20-cm depth in the fall and soil finishing to a 10-cm depth in the spring. A total of 187 kg N ha^{-1} was applied just prior to planting. At SVREC, a disc-ripper (20-cm depth) was used in the fall followed by a Triple K soil finisher (10-cm depth) in the spring. Prior to spring tillage 157 kg N ha^{-1} was applied. No-tillage was used at Springport and 193 kg N ha^{-1} was applied. P and K were applied following soil test recommendations at all locations, and there were no insecticide or fungicide applications. Glyphosate-resistant corn was planted in May or early June depending on the site year in 76-cm rows (Table 1). Corn maturity was 92-day at the MSUAF and SVREC sites, and 96- to 99-day at the Springport sites. Seeding depths ranged from 3.8 to 5.0 cm and seeding rate was 79,000 seeds ha^{-1} at MSUAF and SVREC and 74,100 seeds ha^{-1} at Springport. Glyphosate was applied prior to corn planting and just prior to interseeding at V3 and at V6 corn.

Cover crop species included one species from each of the grass, legume, and brassica classification of cover crops. Annual ryegrass (‘Tillage Rootmax’), crimson clover, and oilseed radish (‘Tillage') (Center Seeds, Sydney, OH; LaCrosse Seed, LaCrosse, WI) were broadcast interseeded at V3 and V6 corn at 18, 18, and 9 kg ha^{-1}, respectively. At MSUAF and SVREC, cover crops were interseeded using a hand-spreader. At Springport, a 36-row vacuum-powered interseeder with drop tubes between corn rows was used to interseed. Interseeding dates varied by site year and occurred from mid-May to early July depending on the corn planting date and corn development stage (Table 1). Herbicides at all locations were applied using a tractor-mounted compressed air sprayer at 178 L ha^{-1} and 207 kPa with TeeJet AIXR11003 nozzles (TeeJet Technologies, Wheaton, IL). In the PRE experiment, herbicides were sprayed one to two days after corn planting in 3 m strips perpendicular to corn rows. At MSUAF and SVREC, cover crops were interseeded in 3 m (four corn rows) strips in the direction of corn planting resulting in 9 m^2 plots. At Springport, cover crops were interseeded in 27 m (36 corn rows) strips in the direction of corn planting resulting in 3 x 27 m^2 plots. In the POST experiment, herbicides were applied at V2 to V3 corn in the direction of corn planting. POST herbicides were applied on the same day as the V3 cover crop interseeding except at the MSUAF 2017 site year, where herbicides were applied one day prior to the V3 interseeding. Cover crop interseeding was perpendicular to corn rows at MSUAF and SVREC, and in the direction of corn rows at Springport. All herbicides examined in the PRE and POST experiments are listed in Table 2. A no herbicide control was included for each cover crop species in both experiments. Plots were visually evaluated for cover crop stand reduction following corn harvest in the October. Evaluations were made between the second and third corn rows of each plot at MSUAF and SVREC. At Springport, 3 to 4 evaluations were taken along the entire length of each plot. Cover crop injury was evaluated as a percentage of stand reduction compared with the no residual herbicide control plots, which were given a value of 0% stand reduction.

Greenhouse Experiment

The effect of PRE and POST herbicides on cover crop biomass was evaluated in a greenhouse experiment. The experiment was a three-factor experiment arranged in a randomized complete block design with four replications and repeated two times. The three factors were: cover crop species, herbicide active ingredient, and herbicide rate. The soil used for this experiment was a steam-sterilized, sandy loam field soil with a pH of 7.4 and 3% SOM collected near Charlotte, MI (42°33'56.04" N, 84°50'08.31" W). Square, 100-cm^2 x 13-cm depth pots were filled with soil and saturated with water. Sixteen seeds of a single cover crop species were seeded on the soil surface in each pot. A thin layer of soil (<5 mm) was applied over the cover crop seeds to avoid directly applying herbicides to the seeds. Herbicides were applied the same day as seeding using a single nozzle, pressurized air spray chamber (Allen Manufacturing, Midland, MI) at 178 L ha^{-1} and 207 kPa with a TeeJet 8001E nozzle. Each herbicide was applied at 1x, 0.5x, and 0.25x the field use rates for the PRE experiment and 1x and 0.5x the field use rates for the POST experiment. Reduced application rates were used to simulate herbicide degradation prior to cover crop seeding in the field. Following herbicide application, pots were surface-watered using a light mist to ensure adequate moisture for germination without displacing seeds. For the remainder of the experiment, pots were individually sub-irrigated to reduce herbicide leaching and prevent movement to other pots. Cover crop species, seed source, and herbicides used were the same as the field studies. At 28 days after planting, the aboveground biomass of cover crops growing in each pot was harvested, dried at 27°C for at least 3 days, and weighed.

Statistical Analysis

Field experiment data were combined over site years and were analyzed using the MIXED procedure in SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2012). Cover crop species, interseeding timing, and herbicide were considered fixed effects, and replication, site year, and rep within site year were considered random effects. Analyses were conducted to determine differences in stand reduction for each herbicide by cover crop species combination. Comparisons of least square means at $p \leq 0.05$ were made if F tests were significant ($p \leq 0.05$) using the SAS pdmix800 macro (Saxton, 1998).

Greenhouse experiment data were combined over the two experiment times for the PRE and POST experiments. Cover crop biomass data for the POST herbicides were analyzed using the MIXED procedure in SAS 9.4. Cover crop species, herbicide, and herbicide rate were considered fixed effects. Experiment time and replication within experiment time were considered random effects. Analyses were conducted to determine differences in dry biomass comparing each herbicide x herbicide rate within each cover crop species to the no herbicide control. Means were compared using the same methods as in the field experiment data. For the PRE herbicides, biomass as a percent of the control was plotted against the application rates with the LL.3 three-parameter log-logistic model using the drc package in R (Equation 1) to determine herbicide rates that would cause 10% and 50% biomass reduction. Ten percent biomass reduction was chosen as a level that a farmer may find acceptable. Fifty percent reduction was used to indicate an unacceptable amount of biomass reduction and herbicides that should not be used with certain cover crops. A three-parameter model provided the best fit for the number of rates used. For dose response curves that did not fit the LL.3 model, the three-parameter log-logistic Weibull model (Equation 2) was used. This only occurred for positive dose response curves, where biomass of herbicide treatments was similar or more than the no herbicide control. The effective dose (ED) function determined the point on the line where a certain application rate resulted in 10% and 50% biomass reduction (R Core Team 2018; Ritz et al. 2015). For the LL.3 model, *f(x)* = biomass reduction, *x* = herbicide rate, *c* = lower limit, *b* = slope of the curve, and *e* = rate at specified biomass reduction (i.e. 10% or 50%). For the Weibull model, *f(x)* = biomass reduction, *x* = herbicide rate, *b* = slope of the curve, and *e* = rate at specified biomass reduction. We did not determine ED values for POST herbicides as only two rates were evaluated in the greenhouse.

$$f(x) = \frac{100-c}{1+\exp(b(\log(x)-\log(e)))} \qquad (1)$$

$$f(x) = d(\exp(-\exp(b(\log(x)-e)))) \qquad (2)$$

Results and Discussion

Annual Ryegrass

The time of annual ryegrass interseeding did not affect the response to herbicides in the PRE and POST field experiments (Tables 3 and 4); therefore, data were combined over the V3 and V6 interseeding timings. In the PRE field experiment, Group 15 herbicides (Mallory-Smith and Retzinger 2003), reduced annual ryegrass stand by more than 60% (Table 3). The Group 2 herbicides, flumetsulam and rimsulfuron, caused moderate stand reductions. In the greenhouse, acetochlor, dimethenamid-P, and pyroxasulfone reduced annual ryegrass biomass by 50% at rates less than field use rate (Table 5). Rimsulfuron, atrazine, S-metolachlor, and isoxaflutole reduced annual ryegrass biomass by 10% when applied at rates less than the field use rate (Table 5). Conversely, clopyralid, saflufenacil, and bicyclopyrone could be used at the field use rates without significant biomass or stand reduction (Tables 3 and 5). In the POST field experiment, acetochlor, dimethenamid-P + topramezone, thiencarbazone + tembotrione, S-metolachlor + mesotrione + glyphosate, and topramezone reduced annual ryegrass stand by 75% or more (Table 4). Atrazine (571 and 1121 g ha^{-1}), bromoxynil, mesotrione, and mesotrione + atrazine (285 g ha^{-1}) did not reduce annual ryegrass stand compared with the no herbicide control. In the greenhouse experiment, only dimethenamid-P + topramezone and S-metolachlor + mesotrione + glyphosate reduced annual ryegrass biomass relative to the no herbicide control at the 0.5x and 1x application rates, while acetochlor reduced annual ryegrass biomass at the 1x rate only (Table 6).

In both the field and greenhouse experiments, acetochlor, dimethenamid-P, pyroxasulfone, and S-metolachlor reduced annual ryegrass stand and biomass. Additionally, acetochlor and premixes containing Group 15 herbicides applied POST to V2 to V3 corn also resulted in losses of annual ryegrass stand and biomass. Group 15 herbicides control many grass weed species (Shaner 2014), and pyroxasulfone is specifically noted for controlling annual ryegrass (Hulting et al. 2012); however, unlike our results Wallace et al. (2017) reported that annual ryegrass could be interseeded at V5 corn following PRE application of dimethenamid-P or acetochlor. Wallace et al. (2017) also reported that annual ryegrass could be interseeded at V5 corn following PRE applications of the Group 2 herbicide, rimsulfuron. This result differs from our results, where the Group 2 herbicides, flumetsulam and rimsulfuron, caused intermediate levels of annual ryegrass stand and biomass reductions. It is not clear why results differ, but climate and soil types may have resulted in differences. Mesotrione caused 17% stand reduction in the field compared with the no herbicide control; which may be acceptable if weeds are controlled (Table 3).

Oilseed Radish

In the PRE field experiment, the Group 2 herbicides, flumetsulam and rimsulfuron, caused the greatest reduction in oilseed radish stand at both interseeding timings (>70%) (Table 3). At the V3 interseeding timing, mesotrione, pyroxasulfone, and acetochlor also reduced oilseed radish stand; whereas at the V6 interseeding timing, pyroxasulfone and saflufenacil were the only other herbicides that caused a reduced stand compared with the no herbicide control. In the greenhouse, atrazine and mesotrione were the only PRE herbicides that reduced oilseed radish biomass by 50% at rates less than the field use rates (Table 5). PRE herbicides that reduced oilseed radish biomass by 10% at rates lower than the field use rates included: atrazine, mesotrione, isoxaflutole, acetochlor, dimethenamid-P, flumetsulam, saflufenacil, and pyroxasulfone (Table 5). In the POST field experiment, the time of interseeding did not affect oilseed radish response to herbicides applied POST to V2 to V3 corn; therefore, data were combined over interseeding timings (Table 4). Atrazine (1121 g ha^{-1}), tembotrione, topramezone, mesotrione + atrazine (571 and 1121 g ha^{-1}), thiencarbazone + tembotrione, and S-metolachlor + mesotrione + glyphosate all resulted in unacceptable oilseed radish stands. In the greenhouse, none of the POST herbicides reduced oilseed radish biomass compared with the no herbicide control (Table 6); however, slight bleaching symptoms (<10%) were observed when any of the Group 27 herbicides, mesotrione, tembotrione, or topramezone were applied (data not shown).

Oilseed radish can be interseeded at V3 or V6 following a PRE application of clopyralid, S-metolachlor, or bicyclopyrone. In the field atrazine and isoxaflutole also did not reduce stand, but when applied in the greenhouse closer to oilseed radish seeding, at least 10% biomass reduction occurred. Atrazine has been used for decades in Michigan, and research has shown that atrazine degrades rapidly in soils where it has been frequently applied (Mueller et al. 2017). Additionally, isoxaflutole degradation is accelerated in biologically active soils (Taylor-Lovell et al. 2002). Greenhouse soils in this experiment were sterilized, so degradation was likely slowed. For acetochlor, dimethenamid-P, or mesotrione delaying oilseed radish interseeding until V6 may reduce injury and biomass reduction. In this experiment, there was variability in oilseed radish injury following a saflufenacil application, with more injury occurring at V6 compared with V3; Yu et al. (2015) found that fall-seeded oilseed radish was not injured by saflufenacil + dimethenamid-P. Seeding oilseed radish at either V3 or V6 following an application of saflufenacil likely causes some stand reduction, but this may be acceptable if weeds are controlled. Following POST applications of atrazine (571 g ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, and dimethenamid-P + topramezone oilseed radish can be interseeded at V3 or V6. Oilseed radish has not been used frequently in other interseeding research; however, research from Missouri where cover crops were seeded in September following applications of PRE and POST herbicides showed that flumetsulam, isoxaflutole, rimsulfuron, and topramezone could cause stand loss or biomass reduction of greater than 30% (Cornelius and Bradley, 2017), so these herbicides also have the potential to cause injury and stand reduction in an interseeded system.

Crimson Clover

Crimson clover emergence in the field was very poor because it was intolerant of dry conditions following broadcast interseeding at all experimental site-years, so no data are presented. In the greenhouse, PRE clopyralid, atrazine, acetochlor, dimethenamid-P, S-metolachlor, and isoxaflutole caused 50% biomass reduction at less than 1x field use rates (Table 5). POST atrazine (1121 g ha^{-1}) at 1 and 0.5x reduced crimson clover biomass by as much as 66% relative to the no herbicide control (Table 6). Dicamba + diflufenzopyr, dimethenamid-P + topramezone, and S-metolachlor + mesotrione + glyphosate also resulted in reduced crimson clover biomass at the 1x rate only (Table 6).

Other researchers have shown successful establishment of crimson clover when drill interseeded in corn (Abdin et al., 1998; Curran et al., 2018; Belfry and Van Eerd, 2016); therefore, the results of the greenhouse experiment could be useful in drill interseeded systems where crimson clover may have better establishment. Our greenhouse results suggest that crimson clover may be interseeded following PRE applications of rimsulfuron, saflufenacil, pyroxasulfone, and POST bromoxynil, fluthiacet, tembotrione, and topramezone. Conflicting results between the tolerance of crimson clover in the PRE and POST experiments with acetochlor and mesotrione, suggest that crimson clover tolerance with these two herbicides should be examined further. These greenhouse results can be used to provide a starting point for further examination of interseeded crimson clover tolerance to PRE and POST herbicides.

Annual ryegrass, crimson clover, and oilseed radish can be interseeded in corn following the application of PRE and POST herbicides with residual activity; however, cover crop species and herbicide combinations should be chosen to prevent cover crop injury, biomass reduction, and stand loss. Herbicide activity and cover crop performance may differ comparing conventional till and no-till management practices. These combinations will be selected based on the weeds that need to be managed and the goals of establishing a cover crop. Annual ryegrass can be interseeded at V3 or V6 following PRE applications of atrazine, clopyralid, saflufenacil, bicyclopyrone, isoxaflutole, and mesotrione, and POST applications of atrazine, bromoxynil, and mesotrione. Oilseed radish can be interseeded at V3 or V6 following PRE applications of clopyralid, atrazine, S-metolachlor, bicyclopyrone, and isoxaflutole and following applications of acetochlor, dimethenamid-P, or mesotrione at V6. Oilseed radish can also be interseeded following POST applications of atrazine (571 g ha^{-1}), bromoxynil, fluthiacet, acetochlor, mesotrione, dicamba + diflufenzopyr, and dimethenamid-P + topramezone oilseed radish can be interseeded at V3 or V6. Oilseed radish should not be interseeded following PRE applications of flumetsulam and POST applications of atrazine (1121 g ha^{-1}) or mixtures containing atrazine. Crimson clover did not establish in this experiment and we do not recommend this species for broadcast interseeding; however, if successfully established, our greenhouse results suggest that crimson clover could be successfully interseeded following PRE applications of rimsulfuron, saflufenacil, pyroxasulfone, and POST applications of bromoxynil, fluthiacet, tembotrione, and topramezone. Crimson clover should not be interseeded following applications of PRE atrazine, S-metolachlor, and acetochlor, and POST atrazine (1121 g ha^{-1}). Additional research in the field should be conducted to confirm these results. Annual ryegrass and oilseed radish can be interseeded in a mixture following applications of PRE clopyralid and bicyclopyrone, and POST bromoxynil and mesotrione. Additionally, this mixture could be interseeded following applications of PRE atrazine and isoxaflutole and POST atrazine (571 g ha^{-1}), but some stand reduction is expected. Farmers must consider weed control and cover crop goals when making these decisions, and some level of cover crop injury may be acceptable to achieve optimal weed control.

APPENDIX

APPENDIX C

CHAPTER 3 TABLES

Table 3.01. Corn planting and cover crop interseeding dates for each site year from 2016 to 2018.

	Preemergence experiment		
Site year	Corn planted	V3 interseeded	V6 interseeded
MSUAF[a] 2016	May 17	June 3	June 22
MSUAF 2017	May 23	June 15	June 23
MSUAF 2018	June 4	June 21	July 15
SVREC[b] 2018	May 9	June 5	June 19
Springport 2016	May 21	June 8	-
Springport 2017	May 31	June 19	June 29
Springport 2018	May 26	June 14	June 21
	Postemergence experiment[c]		
Site year	Corn planted	V3 interseeded	V6 interseeded
MSUAF 2017	May 23	June 17	June 25
MSUAF 2018	May 8	June 1	June 15
SVREC 2018	May 9	June 5	June 19
Springport 2018	May 26	June 14	June 21

[a] Michigan State University Agronomy Farm, East Lansing, MI.
[b] Saginaw Valley Research and Extension Center, Richville, MI.
[c] Postemergence herbicides were applied on the same day of V3 interseeding except at the MSUAF 2017 site year, where herbicides were applied one day prior to the V3 interseeding.

Table 3.02. Preemergence (PRE) and postemergence (POST) herbicide active ingredients, application timings, herbicide sites of action (SOA), and field use rates applied in the field and greenhouse experiments from 2016 to 2018.

Active ingredient	Trade Name	Application timing	SOA	Rate (g ai ha^{-1})
flumetsulam	Python[a]	PRE	2	56
rimsulfuron	Resolve SG[a]	PRE	2	22
clopyralid	Stinger[a]	PRE	4	105
atrazine	AATrex[b]	PRE, POST (0.5x, 1x)[g]	5	1121, 571, 1121
saflufenacil	Sharpen[c]	PRE	14	75
acetochlor	Harness[d], Warrant[d]	PRE, POST	15	2455, 1262
dimethenamid-P	Outlook[c]	PRE	15	942
pyroxasulfone	Zidua[c]	PRE	15	179
S-metolachlor	Dual II Magnum[e]	PRE	15	1424
bicyclopyrone	comp. of Acuron[e]	PRE	27	50
isoxaflutole	Balance Flexx[d]	PRE	27	105
mesotrione	Callisto[e]	PRE, POST	27	210, 105
bromoxynil	Buctril[d]	POST	6	421
fluthiacet	Cadet[f]	POST	14	1.7
tembotrione	Laudis[d]	POST	27	92
topramezone	Armezon[c]	POST	27	18
mesotrione + atrazine	-	POST (0.5x)[g]	27 + 5	105 + 285
mesotrione + atrazine	-	POST (1x)[g]	27 + 5	105 + 509
dicamba + diflufenzopyr	Status[c]	POST	4 + 19	140 + 56
dimethenamid-P + topramezone	Armezon PRO[c]	POST	15 + 27	920 + 17
thiencarbazone + tembotrione	Capreno[d]	POST	2 + 27	27 + 77
S-metolachlor + mesotrione + glyphosate	Halex GT[e]	POST	15 + 27 + 9	1068 + 105 + 1042

[a] Corteva Agriscience, Wilmington, DE
[b] Land O'Lakes, Inc., Arden Hills, MN
[c] BASF Corporation, Florham Park, NJ
[d] Bayer Corporation, Whippany, NJ

Table 3.02 (cont'd)

[e] Syngenta International AG, Basel, Switzerland

[f] FMC Corporation, Philadelphia, PA

[g] Applied at different field use rates as indicated.

Table 3.03. Annual ryegrass and oilseed radish stand reduction (%) caused by preemergence (PRE) herbicides in the field experiment.

	Annual ryegrass[a]	Oilseed radish[b]	
Active ingredient	V3 + V6	V3	V6
	——— stand reduction (%)[c] ———		
flumetsulam	46*	74*	100*
rimsulfuron	33*	73*	74*
clopyralid	6	12	29
atrazine	8	13	18
saflufenacil	4	23	36*
acetochlor	67*	44*	7
dimethenamid-P	71*	28	6
pyroxasulfone	86*	48*	41*
S-metolachlor	68*	27	9
bicyclopyrone	7	6	16
isoxaflutole	6	28	16
mesotrione	17*	56*	15
no herbicide	0	0	0
±SEM[d]	(± 8)	(± 10)	(± 10)

[a] Annual ryegrass data are combined across site years and the V3 and V6 interseeding timings.
[b] Oilseed radish data were combined over site years.
[c] Treatment means followed by an asterisk (*) were significantly greater compared with the no herbicide control at $\alpha = 0.05$ within each column using Fisher's Least Significant Difference.
[d] Standard error of mean (SEM) for mean comparisons.

Table 3.04. Annual ryegrass and oilseed radish stand reduction (%) caused by postemergence (POST) herbicides in the field experiment.[a]

Treatment	Annual ryegrass	Oilseed radish
	——— stand reduction (%)[b] ———	
atrazine (571 g ha^{-1})	14	20
atrazine (1121 g ha^{-1})	12	34*
bromoxynil	13	11
fluthiacet	26*	19
acetochlor	91*	24
mesotrione	9	18
tembotrione	60*	37*
topramezone	76*	44*
mesotrione + atrazine (285 g ha^{-1})	16	59*
mesotrione + atrazine (509 g ha^{-1})	23*	60*
dicamba + diflufenzopyr	48*	31
dimethenamid-P + topramezone	76*	4
thiencarbazone + tembotrione	87*	47*
S-metolachlor + mesotrione + glyphosate	92*	41*
no herbicide	0	0
±SEM[c]	(±9)	(±12)

[a] Data are combined across site years and the V3 and V6 interseeding timings.
[b] Treatment means followed by an asterisk (*) were significantly greater compared with the no herbicide control within each column at $\alpha = 0.05$ using Fisher's Least Significant Difference.
[c] Standard error of mean (SEM) for mean comparisons.

Table 3.05. PRE herbicide rates to cause 10% biomass reduction (BR_{10}) and 50% biomass reduction (BR_{50}) using equations 1 and 2 in the text to annual ryegrass, oilseed radish, and crimson clover in the greenhouse from 2016 to 2018.

		Annual ryegrass		Oilseed radish		Crimson clover	
Active ingredient	Field use rate	BR_{10}	BR_{50}	BR_{10}	BR_{50}	BR_{10}	BR_{50}
	g ai ha^{-1}	% of field use rate[a]					
flumetsulam	56	>100	>100	18.3	>100	0.05	>100
rimsulfuron	22	74.0	>100	>100	>100	89.3	>100
clopyralid	105	>100	>100	>100	>100	13.9	77.4
atrazine	1121	24.6	>100	20.0	86.1	1.9	7.7
saflufenacil	75	>100	>100	0.04	>100	86.3	>100
acetochlor	2455	5.0	11.4	96.0	>100	0.3	7.8
dimethenamid-P	942	3.0	9.3	0.01	>100	18.6	55.5
pyroxasulfone	179	15.5	28.1	79.9	>100	88.5	>100
S-metolachlor	1424	0.8	>100	>100	>100	1.7	24.2
bicyclopyrone	50	>100	>100	>100	>100	0.01	>100
isoxaflutole	105	79.6	>100	0.9	>100	81.0	93.8
mesotrione	210	>100	>100	19.3	91.4	0.01	>100

[a] Rate of herbicide sprayed as a fraction of the field use rate.

Table 3.06. Annual ryegrass, oilseed radish, and crimson clover aboveground biomass reduction caused by postemergence (POST) herbicides in the greenhouse.

Active ingredient		Annual ryegrass	Oilseed radish	Crimson clover
	Rate[a]	——— aboveground biomass (g pot^{-1})[b] ———		
atrazine (571 g ha^{-1})	0.5	0.49	1.25	0.23
	1	0.55	1.31	0.17*
atrazine (1121 g ha^{-1})	0.5	0.45	1.08	0.14*
	1	0.62	1.30	0.09*
bromoxynil	0.5	0.71	1.45	0.36
	1	0.62	1.29	0.46
fluthiacet	0.5	0.77	1.34	0.36
	1	0.73	1.42	0.49
acetochlor	0.5	0.38	1.28	0.49
	1	0.30*	1.36	0.48
mesotrione	0.5	0.59	1.14	0.39
	1	0.51	1.12	0.29
tembotrione	0.5	0.52	1.28	0.43
	1	0.51	1.19	0.31
topramezone	0.5	0.56	1.30	0.39
	1	0.67	1.50	0.42
mesotrione + atrazine	0.5	0.57	0.86	0.38
(285 g ha^{-1})	1	0.67	1.23	0.42
mesotrione + atrazine	0.5	0.68	1.12	0.37
(509 g ha^{-1})	1	0.49	1.17	0.37
dicamba + diflufenzopyr	0.5	0.58	1.03	0.21
	1	0.35	1.27	0.14*
dimethenamid-P +	0.5	0.31*	1.45	0.28
topramezone	1	0.24*	1.21	0.14*
thiencarbazone +	0.5	0.47	1.35	0.28
tembotrione	1	0.55	1.04	0.23
s-metolachlor+	0.5	0.15*	1.26	0.22
mesotrione + glyphosate	1	0.11*	1.13	0.11*
no herbicide		0.63	1.56	0.34
±SEM[c]		(±0.20)	(±0.83)	(±0.14)

[a] Rate of herbicide sprayed as a fraction of the 1x rate.
[b] Treatment means followed by an asterisk (*) were significantly greater compared with the no herbicide control within each column at α = 0.05 using Fisher's Least Significant Difference.
[c] Standard error of mean (SEM) for mean comparisons.

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CHAPTER 4

SOIL HEALTH BENEFITS FROM COVER CROPS INTERSEEDED IN CORN

Abstract

Interseeding cover crops from the V1-V7 corn stages gives farmers an option to incorporate cover crops into corn – soybean rotations when seasonal constraints limit fall establishment. Previous research has yet to examine the impacts of interseeded cover crops on soil health; therefore, the objectives of this research were to determine the effects of interseeded cover crops on crop and soil health and nutrient cycling in the year following interseeding. Field experiments were conducted at the Michigan State University Agronomy Farm (MSUAF) from 2015-2018, and at the Saginaw Valley Research and Extension Center (SVREC) from 2017-2018. Annual ryegrass, crimson clover, oilseed radish, and a mixture of these three species were broadcast interseeded in corn at each of the V1-V7 growth stages in 2015, 2016, and 2017. In April or May in the year following interseeding, soil samples were collected from plots interseeded at V1, V3, V5 in the previous year, as well as the no cover control plots. Soil samples were analyzed for extracellular enzyme activity (EEA), inorganic nitrogen content, and water stable aggregate stability. Corn was planted as an indicator crop and analyzed for carbon and nitrogen content. At MSUAF, corn leaves were sampled at pollination, and at SVREC, corn was sampled at the V3 corn stage. There were no differences in EEA when comparing the no cover crop control to the cover crop treatments. April soil NO_3^- content was lower in plots where annual ryegrass was interseeded, as it was the only cover crop that overwintered. Corn N content at pollination was also lower where annual ryegrass was interseeded at the MSUAF 2018 site only. Short-term changes in nitrogen cycling were evident where there was overwintering annual

ryegrass, suggesting changes in N availability to the successive crop. Many of the benefits of cover cropping may not be evident one year after interseeding; it is likely that changes in soil enzyme activity and microbial community dynamics may require multiple years of cover cropping.

Introduction

Crop rotations in the Midwestern United States are not diverse and are often limited to corn, soybean, and wheat because of commodity demand, farmer knowledge, and equipment costs (Aguilar et al. 2015). Adding cover crops to non-diverse cash crop rotations can improve soil health by increasing microbial activity and diversity, increasing SOM and nutrient cycling (Karlen and Obrycki 2018; Congreves et al. 2015; Tiemann et al. 2015; McDaniel et al. 2014), and altering N mineralization and availability to plants (Sanchez et al. 2001).

Cover crop acreage is increasing in the United States (CTIC, 2017). The number of acres planted to a cover crop increased by 50% from 2012 to 2017 (USDA NASS 2019), but cover crops are still only planted on about 3% of acres. Seeding cost, return on investment, and lack of cover crop variety enhancement are some of the key barriers to cover crop adoption (Wayman et al., 2017). In northern Midwest corn and soybean rotations, cover crop establishment is difficult because of the short growing season in the fall following cash crop harvest; winter-hardy grass species are often the only option, and these can still experience poor germination (Baker and Griffis 2009). One option for expanding cover crop seeding opportunities is to interseed cover crops in corn early in June prior to corn canopy closure. Annual ryegrass (*Lolium multiflorum* Lam.), crimson clover (*Trifolium incarnatum* L.) (Curran et al. 2018; Belfry and Van Eerd 2016; Grabber et al. 2014; Zhou et al. 2000; Abdin et al., 1998; Abdin et al. 1997; Scott et al. 1987), and oilseed radish (*Raphanus sativus* L.) (Belfry and Van Eerd 2016; Roth et al 2015) have been successfully interseeded in corn after the V2 growth stage with no impact on corn grain yield.

Cover crops provide a variety of environmental and cropping system benefits. A recent farmer survey indicated that improving soil health was the greatest driver of using cover crops (CTIC-SARE 2017). Researchers have shown that long-term cover cropping can increase SOM by over 10% across a wide range of production systems (McDaniel et al. 2014). SOM is critical for soil structure, improving water infiltration and holding capacity, and supporting soil biota, which in turn releases nutrients for plant uptake (Bardgett 2005). In particular, higher levels of SOM support greater microbial biomass (Schnurer et al. 1985), which is important because soil microbes are critical for decomposing residues and building SOM (Miltner et al. 2011). Microbes mediate nutrient cycling and are especially important controllers of plant N availability (Cavigelli et al. 2013).

While there are numerous indicators of soil health in cropping systems, extracellular enzyme activity (EEA), soil NH_4^+ and NO_3^- concentrations, and soil aggregate stability were the indicators measured in our research. Enzymes are produced and used by microbes to breakdown and mineralize organic compounds in the soil to obtain both energy (C) and nutrients (e.g. N and P). EEA can serve as an indicator of microbial activity levels as well as nutrient demands or limitations. NH_4^+ and NO_3^- are the end products of microbially mediated N transformations in soils and are forms of N readily available for plant uptake that can provide important insight into N cycling in cropping systems (Tiemann and Billings 2011). For example, diversification of cropping systems through cover crop addition and adding cash crops into rotations has been shown to improve N availability and crop yields (Smith et al. 2008). Importantly, NO_3^-, which is produced by the nitrification of NH_4^+, can be taken up by crops, but can also lead to N loss as it is leached through the soil profile, or lost through gaseous efflux during the process of denitrification. The ultimate fate of inorganic N is largely related to climatic conditions at various times throughout the year and whether there is a crop present to utilize the available N. Finally, water stable aggregates are a representative of measure of soil structure that is directly related to SOM and microbial biomass and activity. Microbial products (e.g. hyphae and polysaccharides) as well as SOM bind soil particles together to form soil aggregates, which helps determine pore space size and connectivity, influencing air and water movement, as well as the activity of soil biota (Bardgett 2005). Air and water movement in soil that is related to aggregate stability is a critical determinant of microbial activities, EEA as well as N transformations. In particular, N loss pathways are controlled by water movement, as NO_3^- leaching and the anaerobic process of denitrification are tightly coupled with air and water movement.

Previous cover crop interseeding research has focused primarily on agronomic variables such as cover crop establishment, biomass production, and competitiveness with grain corn; however, it is imperative to understand how interseeded cover crops affect soil health in the short term (the year of and year following cover cropping) and in the long term. The objectives of this research were to examine EEA, soil nitrogen concentrations, and aggregate stability as indicators of soil health and nutrient cycling the year following cover crop interseeding; additionally, the effects of nutrient cycling in the year following interseeding was assessed by planting corn as an indicator crop.

Materials and Methods

Corn and Cover Crop Management

Field experiments were conducted in 2015-2016, 2016-2017, and 2017-2018 at the Michigan State University Agronomy Farm (MSUAF) in East Lansing, MI (42°42'38.64" N, 84°28'16.65" W) on an Aubbeenaubbee-Capac sandy loam (fine-loamy, mixed, active, mesic aeric epiaqualfs; fine-loamy, mixed, active, mesic aquic glossudalfs) in years 1 and 3 and a Conover loam (fine-loamy, mixed, active, mesic aquic hapludalfs) in year 2. Research was also conducted in 2017-2018 at the Saginaw Valley Research and Extension Center (SVREC) in Richville, MI (42°17'59.45" N, 83°41'51.47" W) on a Tappan-Londo loam (fine-loamy, mixed, active, calcareous, mesic typic epiaquolls; fine-loamy, mixed, semiactive, mesic aeric glossaqualfs). Soil organic matter ranged between 2.8-2.9% at MSUAF sites and 3.0% at SVREC. The experimental design was a split-plot with four replications; cover crop species was the main plot and interseeding timing the subplot. Plot size was 3 m wide (4 corn rows) and 12 m long. Cover crop species included annual ryegrass, oilseed radish (var. Tillage Radish®), and crimson clover with NitroCoat® seed coating (34% by weight), and a mixture of the three species (Center Seeds, Sydney, OH). Interseeding rates were 18 kg ha^{-1} for annual ryegrass, 9 kg ha^{-1} for oilseed radish, 18 kg ha^{-1} of coated seed for crimson clover, and 11 kg ha^{-1}, 2 kg ha^{-1}, and 2 kg ha^{-1} of annual ryegrass, oilseed radish, and crimson clover, respectively, for the mixture. The mixture was commercially available as "PeakBlend Indy" (Center Seeds). Seeds per square meter of the single species were 829, 75, and 355 for annual ryegrass, oilseed radish, and crimson clover, respectively. Interseeding timings were based on the corn growth stage measured by the leaf collar method (Abendroth et al., 2011) and included the V1 (MSUAF 2015 only), V2, V3, V4, V5, V6, and V7 (excluding MSUAF 2015) growth stages.

At each MSUAF site year, fields were chisel plowed in the fall prior to the experiment and soil finished in the spring using a Kongskilde Triple K soil finisher (Kongskilde Agriculture, Albertslund, Denmark) just prior to planting. Nitrogen as urea (CH_4N_2O) was broadcast prior to tillage and incorporated at a rate of 155 kg N ha^{-1}. An additional 32 kg ha^{-1} of N as urea and ammonium nitrate (NH_4NO_3), P as P_2O_5, and K as K_2O were applied in a 5 x 5-cm band as starter at planting. At SVREC, tillage included a disc ripper in the fall prior to the experiment followed by a Kongskilde Triple K soil finisher in the spring prior to planting. Nitrogen as urea at 157 N kg ha^{-1} was applied prior to planting. At each site year, glyphosate (N-(phosphonomethyl)glycine)-resistant corn was planted in late-April to mid-May using a four-row corn planter in 76-cm rows. Seeding depth was 3.8 cm at MSUAF and 5 cm at SVREC and the seeding rate in all site years was 79,000 seeds ha^{-1}.

Cover crops were broadcast interseeded at the V1-V7 corn growth stages using a hand-spreader between the first and fourth corn rows so that three interrow spaces were interseeded. Interseeding occurred from mid-May to late June and dates varied by site year depending on the corn planting date and corn development stage. Glyphosate at 0.84 kg ae ha^{-1} was applied the day of each interseeding using a tractor-mounted, compressed air sprayer to control emerged weeds. A weed-free control plot was included to determine corn grain yield in the absence of weeds or cover crops; a plot with no cover crops and no weed control (weedy) was also included.

Soil Sampling and Analyses

In the spring (April/May), two 7.6 cm by 15 cm deep soil cores were taken from the area between the center two corn rows within each of the V1 (2016 only), V2 (2016 and 2018), V3, V5 and no cover crop control plots. The activity of seven extracellular enzymes was assessed using similar methods from Tiemann and Billings (2011). Soils were homogenized in deionized water rather than a buffer solution to maintain extant soil pH. Briefly, 1 g soil was homogenized with a hand-held blender in 125 ml DI water. Soil slurries were pipetted into 96-well microplates with appropriate substrates labeled with the fluorescing molecules methylumbeliferyl (MUB) or metlylcoumarin (MC), with both positive and negative controls. We created a standard curve using four concentration levels of MUB or MC. We measured β-1,4-glucosidase (BG) and cellobiohydrolase (CBH) activities to assess labile C acquisition; phenol oxidase and peroxidase activities to assess recalcitrant carbon acquisition; leucine amino peptidase (LAP), β-1-4-N-acetylglucosaminidase (NAG), and urease activities to assess N mineralization and acquisition and; phosphate-monoester phosphohydrolase (PHOS) activity to assess P mineralization and acquisition. Additionally, NO_3^- and NH_4^+ were extracted from 8 g subsamples of the same soil cores using 40 ml of 0.5 M K_2SO_4, with resulting inorganic N concentrations measured using colorimetric microplate assays (Sinsabaugh et al. 2000; Doane and Horwath 2003). All fluorescence and absorbance measurements for determination of EEA and inorganic N content were read on a Biotek Synergy HT1 plate reader (Biotek, Winooski, VT). Finally, water stable aggregates were assessed from 100 g air-dried soil subsamples using a rotary sieve shaker (Retsch AS200) as described by Tiemann and Grandy (2015). Three aggregate size fractions were obtained, <53 µm, 53-250 µm, and 250 µm-2 mm.

Indicator Crop

Following soil sampling, overwintering cover crops were terminated using glyphosate. Corn was then planted in May in the same fields (the year following cover crop interseeding) using a no-till corn planter in 76-cm rows at a population of 79,000 seeds ha^{-1}. No fertilizer was applied in order to measure differences in corn tissue tests associated with the previous year's cover crops treatments. At pollination (MSUAF 2016, 2018) and V3 (SVREC 2018), the corn ear leaf from 10 corn plants per plot was placed in paper bags, dried at 80°C for at least 4 days, and then ground to <1mm using a Christy and Norris grinding mill (Christy Turner Ltd., Ipswich, Suffolk, UK). Samples were analyzed for carbon and nitrogen content using a Costech Elemental Analyzer (Costech Analytical Technologies, Inc., Valencia, CA) and acetanilide was used for the standard comparison. No further measurements were taken from the corn following ear leaf sampling.

Statistical Analyses

Soil EEA, inorganic N content, and aggregate stability, as well as the nutrient status of the legacy corn crop, were analyzed using PROC MIXED in SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2012). Site years were run individually when *F* tests for site year were significant ($P \leq 0.05$). Cover crop species, interseeding timing, and the interaction of the two were considered fixed effects, and rep, site year (when not significant), and rep within site year were considered random effects. Analyses were conducted to determine differences in EEA, inorganic N content, aggregate stability, and corn nutrient status as affected by changes in cover crop species or interseeding timing. Comparisons of least square means at $P \leq 0.05$ were made if *F* tests were significant ($P \leq 0.05$) using *t* tests conducted by the SAS pdmix800 macro (Saxton, 1998). Reported treatment differences were significant at $P \leq 0.05$, unless otherwise noted. EEA data were normalized by dividing each measurement by the highest measured activity for each enzyme. A factor analysis was performed on these data, and the factor scores were analyzed using PROC MIXED comparing cover crops and interseeding timings within site years.

Results

Soil Inorganic Nitrogen and Aggregation

At the MSUAF 2016 site, there was no effect of cover crop species on soil NH_4^+ and NO_3^- content (Table 4.01); however, total soil inorganic N in plots where annual ryegrass was interseeded was 3.4 µg N g soil^{-1} which was less than plots seeded with crimson clover and oilseed radish (5.08 and 4.98 µg N g soil^{-1}, respectively) (Figure 4.01). At both the MSUAF 2018 and SVREC 2018 sites, there were no differences in NH_4^+, NO_3^-, or total inorganic N when comparing cover crop species (Table 4.01). Combined across cover crop species at the MSUAF 2016 site, soil NO_3^- and total inorganic N content were highest in plots interseeded at the V1 corn stage compared with the V3 and V5 corn stages and the no cover control (Table 4.02). At the SVREC 2018 site, total inorganic N was marginally significant (P-value = 0.0716) comparing interseeding timings with the V1 timing having greater N compared with the V5 interseeding timing (Figure 4.01). There were no differences in soil inorganic N content comparing interseeding timings at the MSUAF 2018 site year (Tables 4.01, 4.02; Figure 4.01). Finally, cover crop species did not cause changes in soil aggregate MWD compared with the no cover crop control when cover crop species and interseeding timings are compared (Tables 4.03 and 4.04).

Extracellular Enzyme Activity

There were no differences in EEA when comparing cover crops with each other or with the no cover crop control (Tables 4.05, 4.07, 4.09, 4.11). At the MSUAF 2016 site, the C:N of EEA was greatest for the no cover crop control plots compared with all cover crop species (Table 4.13). The P:N of the no cover crop control plots was also higher compared with annual ryegrass and oilseed radish plots (Table 4.13). Comparing interseeding timings, combined over cover crop species, there were no differences in EEA at the MSUAF 2018 and SVREC 2018 sites (Tables 4.06, 4.08, 4.10, 4.12). At the MSUAF 2016 site, LAP activity was higher at the V1 interseeding timing compared with the V5 interseeding timing and no cover control; additionally, the V3 interseeding timing was higher compared with the no cover control (Table 4.14). Activity of PER at the MSUAF 2016 site was higher for the V5 interseeding timing and no cover control compared with V1 and V3 interseeding timings (Table 4.14). There were no differences at the MSUAF 2018 and SVREC 2018 sites comparing C:N and P:N of EEA. At the MSUAF 2016 site, the no cover control had greater EEA C:N compared with the V1 and V3 interseeding timings; P:N was higher in the no cover control compared with V1 and V5 interseeding timings (Table 4.12).

Factor analysis using normalized enzyme activities found two orthogonal factors that corresponded to 61, 65, and 88% of the variation for MSUAF 2016, MSUAF 2018, and SVREC 2018, respectively. Across cover crop species and interseeding timings for MSUAF 2016, Factor 1 was most positively correlated with BG, CBH, NAG, and PHOS activities, though correlations were not greater than 0.3; Factor 2 was highly correlated with PER activity (Figure 4.03). Factor 2 scores were marginally significantly influenced by cover crop species (*P*-value = 0.0681) with the highest scores associated with the no cover control, indicating the highest PER activity. Factor 2 scores were significantly influenced by interseeding timing, with the highest scores, and PER activity, occurring in the no cover control. Across cover crop species and interseeding timings for MSUAF 2018, Factor 1 was most positively correlated with PER activity, and Factor 2 was most positively correlated with BG, CBH, and UREASE activity; however, the highest correlation was 0.38 (Figure 4.03). Factor 1 scores were marginally significantly influence by cover crop species (*P*-value = 0.0646) with oilseed radish having higher scores relative to annual ryegrass and the mixture. Across cover crop species and interseeding timings for SVREC 2018, Factor 1 was positively correlated with CBH and negatively correlated with NAG, LAP, PHEN and PER, and Factor 2 was positively correlated with PHOS and PER, and negatively correlated with BG and PHEN (Figure 4.03); however, there were no differences comparing factors scores for either cover crop species or interseeding timing.

Legacy Corn C and N

Cover crop species had no effect on legacy corn C and N content at the MSUAF 2016 and SVREC 2018 sites (Table 4.15). At MSUAF 2018, corn leaf C was higher where crimson clover was interseeded compared with annual ryegrass and the no cover control; additionally, carbon content was higher where oilseed radish as interseeded the previous year compared with the no cover control (Table 4.15). Corn N content was lowest in the annual ryegrass and no cover control (Table 4.15). This translated to a C:N of 27:1 for annual ryegrass, which was significantly greater than crimson clover and oilseed radish, with C:N of 25:1 and 25:1, respectively (Figure 4.02). Comparing interseeding timings combined across cover crop species, C content did not differ at any site year (Table 4.16). N content was higher where cover crops were interseeded at V5 compared with the no cover control at the MSUAF 2016 site (Table 4.16). Similarly, at MSUAF 2018, N content was higher where cover crops were interseeded at V5 compared with the V3 and no cover control (Table 4.16). These differences translated into a lower C:N for the V5 interseeding timing compared with the no cover control at MSUAF 2016, and a lower C:N for the V5 interseeding timing compared with the V3 interseeding timing and no cover control at MSUAF 2018 (Table 4.16; Figure 4.02). There were no differences in N or C:N at the SVREC 2018 site (Table 4.16).

Discussion

Differences in soil inorganic N content were likely driven by cover crop and weed biomass in the spring following the interseeding year. At the MSUAF 2016 site, there was less soil inorganic N in plots where annual ryegrass was interseeded; annual ryegrass was the only cover crop that overwintered and held N, whereas crimson clover and oilseed radish winterkilled and released N into the soil. The V1 interseeding at MSUAF 2016 had the highest soil N content compared with the V3 and V5 interseedings; annual ryegrass biomass was much lower at the V1 timing compared with the V3 and V5 timings (data not shown). At the SVREC 2018 location, cover crop and weed biomass in the V1 interseeding were greater than biomass in the V5 interseeding, and this may have resulted in greater N release as the cover crops and weeds decomposed. Our findings are consistent with research results from the Mid-Atlantic U.S. where soils with overwintering cover had less NO_3^- when sampled in the spring compared with soils where cover crops winterkilled; this research also found that cover crops caused minimal changes in soil NH_4^+ content, which aligns with our results (Dean and Weil 2009).

Overall, cover crop species and interseeding timings had minimal effects on EEA after only one year of interseeding. We had hypothesized that the intensively cultivated soils where the experiments were established would quickly respond to the addition of cover crops. Indeed, we did see marginal changes in microbial community function at the site with the lowest soil quality (MSUAF 2016) and it has been shown previously that increasing organic amendment (i.e. green manure) or cropping system diversity can have impacts within 1-2 years (Kallenbach and Grandy, 2013; McDaniel et al. 2014). Although we observed major differences in EEA only between sites and years, we would expect the differences to widen with successive years of interseeding. Labile C acquisition enzyme activity of BG was often similar to previous research results from the Midwest and southern Canada (Stott et al., 2010); total labile C acquisition (BG + CBH) was similar at some locations in our experiment compared with recent research from Michigan (~315 nmol activity g^{-1} soil h^{-1}) (Tiemann et al., 2015). Total inorganic nitrogen content in our research was similar to or greater than levels reported in previous research (122 nmol activity g^{-1} soil h^{-1}) (Tiemann et al., 2015); NAG levels at the MSUAF locations were similar to those reported in Southwest Michigan previously, but levels at SVREC were much higher (Wickings et al., 2016; McDaniel et al., 2014). PHOS activity at the MSUAF 2016 location was similar to two previous experiments in Michigan, but much lower in 2018 (Wickings et al., 2016; McDaniel et al., 2014); our PHOS levels were lower compared with Tiemann et al. (2015) where levels were ~350 nm of activity g^{-1} soil h^{-1}. Recalcitrant carbon acquisition enzyme activity was highly variable between sites but fell within ranges found in previous research (Wickings et al., 2016; Tiemann et al., 2015; McDaniel et al., 2014). Previous research has also demonstrated that it is difficult to determine differences in enzyme activity based on cropping system, because site-specific interactions between plant species and their environment drive more dramatic annual and seasonal changes in enzyme activity (Tiemann and Grandy 2015; Berg and Smalla, 2009).

Our results show that cover crops species can have variable effects on legacy crops, and the effects are likely based on location and environmental conditions. Annual ryegrass caused reduced corn nitrogen content at the MSUAF 2018 site compared with crimson clover and oilseed radish. This resulted in a higher C:N in corn following annual ryegrass. While not significant, the MSUAF 2016 and SVREC 2018 locations showed similar trends (Table 4.15). Our results support previous research where increased cover crop biomass in the spring reduced N availability to a proceeding cash crop (Finney et al. 2016; Schipanski et al. 2014) and sometimes reduced crop yield (Krueger et al., 2011). In contrast, after eight years of cereal rye cover cropping, corn yield was not reduced despite reduced soil inorganic N content (Snapp and Surapur, 2018). Corn following crimson clover and oilseed radish had slightly higher nitrogen content compared with the no cover control (Table 4.15), indicating the potential for these crops to have a nitrogen benefit to a proceeding cash crop. Nitrogen fixing species such as clover provide additional soil N compared with no cover crops (Schipanski et al. 2014).

Conclusions

This research evaluated the effects of cover cropping for only one growing season; it is established in the literature that effects are more pronounced after multiple years of growing cover crops (Basche et al. 2016; Mbuthia et al. 2015; Sainju et al. 2002; Kuo et al. 1997). Microbial community structure was enhanced in a 31-year cover cropping study (Mbuthia et al., 2015), while nitrogen cycling was improved in corn over a seven-year period of cover cropping (Gabriel et al., 2016). Conducting this research for multiple seasons could lead to greater changes in the variables measured. Cover crop biomass production in our research was sometimes lower, but often similar compared with other published research in the Upper Midwest and mid-Atlantic states (Curran et al., 2018; Youngerman et al., 2018; Roth et al., 2015; Noland et al., 2018). Spring biomass production was 384, 8, and 0 kg ha^{-1} for annual ryegrass, crimson clover, and oilseed radish (data not shown). Biomass production greater than 1000 kg ha^{-1} was required to suppress weeds in previous research (Baraibar et al., 2018), so we do not expect that cover crops would suppress weeds at the levels of biomass produced in our experiment.

APPENDIX

APPENDIX D

CHAPTER 4 TABLES AND FIGURES

Table 4.01. Effects of cover crop species on soil inorganic nitrogen (NH_4^+ and NO_3^-) content for each site in 2016 and 2018 combined over interseeding timings.

	MSUAF 2016			MSUAF 2018			SVREC 2018		
Cover Crop	NH_4^+	NO_3^-	TIN[a]	NH_4^+	NO_3^-	TIN[a]	NH_4^+	NO_3^-	TIN[a]
		µg N g soil^{-1}			µg N g soil^{-1}			µg N g soil^{-1}	
Annual ryegrass	1.53 a[c]	1.87 a	3.39 b	0.24 a	2.81 a	3.06 a	0.23 a	5.07 a	5.30 a
Crimson clover	1.83 a	3.25 a	5.08 a	0.44 a	3.72 a	4.16 a	0.31 a	7.41 a	7.72 a
Oilseed radish	1.91 a	3.05 a	4.98 a	0.66 a	3.53 a	4.19 a	0.35 a	6.63 a	6.99 a
Mixture	-	-	-	0.58 a	3.98 a	4.56 a	0.34 a	6.53 a	6.87 a
No cover	1.80 a	2.10 a	3.92 ab	0.11 a	3.73 a	3.84 a	0.31 a	5.28 a	5.59 a
±SEM[b]	±0.39	±0.57	±0.76	±0.27	±0.63	±0.82	±0.08	±1.05	±1.06

[a]TIN = Total inorganic nitrogen; the sum of NH_4^+ and NO_3^-.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.02. Effects of interseeding timing on soil inorganic nitrogen (NH_4^+ and NO_3^-) content for each site in 2016 and 2018 combined over cover crop species.

	MSUAF 2016			MSUAF 2018			SVREC 2018		
Cover Crop	NH_4^+	NO_3^-	TIN[a]	NH_4^+	NO_3^-	TIN[a]	NH_4^+	NO_3^-	TIN[a]
		μg N g soil^{-1}			μg N g soil^{-1}			μg N g soil^{-1}	
V1	1.91 a[c]	4.24 a	6.17 a	0.40 a	3.28 a	3.68 a	0.28 a	7.78 a	8.06 a
V3	1.61 a	2.12 b	3.74 b	0.51 a	3.44 a	3.96 a	0.37 a	6.12 a	6.49 a
V5	1.69 a	1.64 b	3.34 b	0.53 a	3.75 a	4.28 a	0.27 a	5.33 a	5.60 a
No cover	1.80 a	2.09 b	3.91 b	0.11 a	3.45 a	3.84 a	0.31 a	5.28 a	5.59 a
±SEM[b]	±0.39	±0.53	±0.71	±0.24	±0.56	±0.74	±0.08	±0.96	±0.97

[a]TIN = Total inorganic nitrogen; the sum of NH_4^+ and NO_3^-.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.03. Effects of cover crop species on the mean weight diameter (MWD) of soil particles for each site in 2016 and 2018 combined over interseeding timings.

Cover Crop	MSUAF 2016	MSUAF 2018	SVREC 2018
		MWD	
		mm	
Annual ryegrass	1.06 a[b]	1.23 a	1.07 a
Crimson clover	1.08 a	1.27 a	1.00 a
Oilseed radish	1.01 a	1.02 a	1.13 a
Mixture	-	1.26 a	1.06 a
No cover	1.08 a	1.09 a	1.22 a
±SEM[a]	±0.10	±0.14	±0.07

[a]Standard error of the mean

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.04. Effects of interseeding timing the mean weight diameter (MWD) of soil particles for each site in 2016 and 2018 combined over cover crop species.

Interseeding Timing	MSUAF 2016	MSUAF 2018	SVREC 2018
		MWD	
		mm	
V1	0.99 a[b]	1.18 a	1.04 a
V3	1.03 a	1.09 a	1.00 a
V5	1.14 a	1.31 a	1.15 a
No cover	1.07 a	1.09 a	1.22 a
±SEM[a]	±0.10	±0.12	±0.07

[a]Standard error of the mean.

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.05. Effects of cover crop species on carbon acquisition enzyme activity for each site in 2016 and 2018 combined over interseeding timings.

Cover Crop	MSUAF 2016			MSUAF 2018			SVREC 2018		
	BG	CBH	TC[a]	BG	CBH	TC[a]	BG	CBH	TC[a]
	nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}		
Annual ryegrass	288 a[c]	147 a	436 a	166 a	129 a	296 a	200 a	68 a	267 a
Crimson clover	314 a	167 a	481 a	163 a	124 a	287 a	192 a	60 a	252 a
Oilseed radish	305 a	147 a	452 a	167 a	130 a	296 a	225 a	81 a	307 a
Mixture	-	-	-	170 a	131 a	301 a	214 a	74 a	288 a
No cover	283 a	135 a	418 a	189 a	130 a	319 a	218 a	76 a	294 a
±SEM[b]	±28	±19	±45	±10	±24	±30	±21	±15	±37

[a]TC = Total activity of carbon acquisition enzymes; sum of BG and CBH.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.06. Effects of interseeding timing on the activity of carbon acquisition enzymes for each site in 2016 and 2018 combined over cover crop species.

	MSUAF 2016			MSUAF 2018			SVREC 2018		
Cover Crop	BG	CBH	TC[a]	BG	CBH	TC[a]	BG	CBH	TC[a]
	nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}		
V1	319 a[c]	164 a	484 a	153 b	120 a	273 a	211 a	68 a	279 a
V3	270 a	128 a	399 a	170 ab	131 a	300 a	214 a	76 a	291 a
V5	317 a	168 a	485 a	175 a	135 a	310 a	198 a	68 a	266 a
No cover	282 a	135 a	418 a	189 a	130 a	319 a	218 a	76 a	294 a
±SEM[b]	±28	±19	±46	±10	±23	±28	±19	±15	±35

[a]TC = Total activity of carbon acquisition enzymes; sum of BG and CBH.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.07. Effects of cover crop species on nitrogen acquisition enzyme activity for each site in 2016 and 2018 combined over interseeding timings.

	MSUAF 2016				MSUAF 2018				SVREC 2018			
Cover Crop	NAG	LAP	UREASE	TN[a]	NAG	LAP	UREASE	TN[a]	NAG	LAP	UREASE	TN[a]
	nmol activity g^{-1} soil h^{-1}				nmol activity g^{-1} soil h^{-1}				nmol activity g^{-1} soil h^{-1}			
Annual ryegrass	95 a[c]	67 a	82 a	244 a	39 a	36 a	117 a	193 a	39 a	121 a	131 a	292 a
Crimson clover	100 a	75 a	68 a	243 a	38 a	30 a	108 a	177 a	37 a	139 a	127 a	303 a
Oilseed radish	99 a	68 a	75 a	242 a	42 a	33 a	102 a	177 a	47 a	121 a	129 a	297 a
Mixture	-	-	-	215 a	48 a	40 a	112 a	199 a	44 a	117 a	130 a	291 a
No cover	85 a	57 a	73 a	26	43 a	34 a	126 a	203 a	40 a	123 a	125 a	288 a
±SEM[b]	±20	±29	±9	±45	±6	±9	±14	±22	±16	±13	±13	±36

[a]TN = Total activity of nitrogen acquisition enzymes; sum of NAG, LAP, and UREASE.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.08. Effects of interseeding timing on the activity of nitrogen acquisition enzymes for each site in 2016 and 2018 combined over cover crop species.

Cover Crop	MSUAF 2016				MSUAF 2018				SVREC 2018			
	NAG	LAP	UREASE	TN[a]	NAG	LAP	UREASE	TN[a]	NAG	LAP	UREASE	TN[a]
	nmol activity g^{-1} soil h^{-1}				nmol activity g^{-1} soil h^{-1}				nmol activity g^{-1} soil h^{-1}			
V1	93 a[c]	78 a	82 a	253 a	35 a	35 a	108 a	177 a	39 a	133 a	133 a	305 a
V3	92 a	71 ab	68 a	230 a	38 a	39 a	108 a	185 a	46 a	124 a	127 a	297 a
V5	110 a	62 bc	75 a	246 a	51 a	31 a	113 a	195 a	40 a	117 a	128 a	285 a
No cover	85 a	57 c	73 a	215 a	43 a	34 a	126 a	203 a	40 a	123 a	125 a	287 a
±SEM[b]	±20	±29	±9	±26	±5	±9	±13	±20	±16	±12	±13	±36

[a]TN = Total activity of nitrogen acquisition enzymes; sum of NAG, LAP, and UREASE.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.09. Effects of cover crop species on phosphorus acquisition enzyme activity for each site in 2016 and 2018 combined over interseeding timings.

Cover Crop	MSUAF 2016	MSUAF 2018	SVREC 2018
		PHOS	
		nmol activity g^{-1} soil h^{-1}	
Annual ryegrass	207 a[b]	22 a	98 a
Crimson clover	236 a	19 a	110 a
Oilseed radish	215 a	17 a	91 a
Mixture	-	27 a	85 a
No cover	238 a	19 a	77 a
±SEM[a]	±32	±4	±22

[a]Standard error of the mean.

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.10. Effects of interseeding timing on phosphorus acquisition enzyme activity for each site in 2016 and 2018 combined over cover crop species.

	MSUAF 2016	MSUAF 2018	SVREC 2018
Interseeding Timing		PHOS	
		nmol activity g^{-1} soil h^{-1}	
V1	221 a[b]	21 a	101 a
V3	212 a	22 a	92 a
V5	225 a	22 a	94 a
No cover	238 a	19 a	77 a
±SEM[a]	±32	±4	±22

[a]Standard error of the mean.

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.11. Effects of cover crop species on recalcitrant carbon acquisition enzyme activity for each site in 2016 and 2018 combined over interseeding timings.

	MSUAF 2016			MSUAF 2018			SVREC 2018		
Cover Crop	PER	PHEN	NETPER[a]	PER	PHEN	NETPER[a]	PER	PHEN	NETPER[a]
	nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}		
Annual ryegrass	342 a[c]	0 a	342 a	1084 a	0 a	980 a	854 a	796 a	370 a
Crimson clover	340 a	18 a	321 a	1344 a	18 a	1325 a	956 a	712 a	401 a
Oilseed radish	335 a	0 a	335 a	1399 a	18 a	1381 a	839 a	409 a	547 a
Mixture	-	-	-	1122 a	4 a	1121 a	912 a	352 a	646 a
No cover	446 a	1 a	445 a	1146 a	0 a	1146 a	939 a	278 a	662 a
±SEM[b]	±226	±10	±225	±226	±12	±240	±338	±346	±188

[a]NETPER = Total activity of recalcitrant carbon acquisition enzymes; peroxidase minus phenoloxidase.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.12. Effects of interseeding timing on the activity of carbon acquisition enzymes for each site in 2016 and 2018 combined over cover crop species.

	MSUAF 2016			MSUAF 2018			SVREC 2018		
Cover Crop	PER	PHEN	NETPER[a]	PER	PHEN	NETPER[a]	PER	PHEN	NETPER[a]
	nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}			nmol activity g^{-1} soil h^{-1}		
V1	294 b[c]	19 a	275 b	1257 a	19 a	1156 a	871 a	715 a	362 a
V3	298 b	0 a	298 b	1034 a	12 a	1023 a	812 a	543 a	436 a
V5	423 a	0 a	423 a	1429 a	0 a	1429 a	996 a	445 a	674 a
No cover	446 a	1 a	445 a	1146 a	0 a	1146 a	939 a	278 a	662 a
±SEM[b]	±226	±10	±226	±217	±11	±228	±328	±323	±168

[a]NETPER = Total activity of recalcitrant carbon acquisition enzymes; peroxidase minus phenoloxidase.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.13. Effects of cover crop species on the ratio of carbon acquisition enzyme to both nitrogen and phosphorus acquisition enzyme activity.

	MSUAF 2016		MSUAF 2018		SVREC 2018	
Cover Crop	CN	PN	CN	PN	CN	PN
Annual ryegrass	3.4 b[b]	0.9 b	8.4 a	0.1 a	3.5 a	0.3 a
Crimson clover	3.4 b	1.0 ab	9.6 a	0.1 a	4.2 a	0.3 a
Oilseed radish	3.5 b	0.9 b	10.2 a	0.1 a	3.5 a	0.3 a
Mixture	-	-	8.1 a	0.1 a	3.7 a	0.3 a
No cover	4.2 a	1.2 a	7.8 a	0.1 a	4.2 a	0.3 a
±SEM[a]	±1.1	±0.2	±1.7	±0.02	±0.8	±0.04

[a]Standard error of the mean.

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.14. Effects of interseeding timing on the ratio of carbon acquisition enzyme to both nitrogen and phosphorus acquisition enzyme activity combined over cover crop species.

	MSUAF 2016		MSUAF 2018		SVREC 2018	
Cover Crop	C:N	P:N	C:N	P:N	C:N	P:N
V1	3.3 b[b]	1.0 b	9.6 a	0.1 a	3.4 a	0.3 a
V3	3.2 b	1.1 ab	8.0 a	0.1 a	3.2 a	0.3 a
V5	3.7 ab	0.9 b	9.7 a	0.1 a	4.5 a	0.3 a
No cover	4.2 a	1.2 a	7.8 a	0.1 a	4.2 a	0.3 a
±SEM[a]	±1.1	±0.2	±1.6	±0.02	±0.8	±0.04

[a]Standard error of the mean.

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.15. Effects of cover crop species on legacy corn crop tissue C and N content for each site in 2016 and 2018 combined over interseeding timings.

	MSUAF 2016			MSUAF 2018			SVREC 2018[a]		
Cover Crop	C	N	C:N	C	N	C:N	C	N	C:N
	%			%			%		
Annual ryegrass	44.80 a[c]	2.14 a	21.0 a	44.57 bc	1.70 c	26.7 a	43.61 a	3.51 a	12.5 a
Crimson clover	44.92 a	2.21 a	20.3 a	44.83 a	1.88 a	24.5 b	44.18 a	3.67 a	12.2 a
Oilseed radish	44.65 a	2.22 a	20.2 a	44.71 ab	1.85 ab	24.7 b	43.93 a	3.65 a	12.1 a
Mixture	-	-	-	-	-	-	43.95 a	3.78 a	11.7 a
No cover	44.21 a	1.99 a	22.3 a	44.47 c	1.65 bc	27.0 ab	44.93 a	3.82 a	11.8 a
±SEM[b]	±0.27	±0.06	±0.8	±0.10	±0.13	±0.6	±0.36	±0.12	±0.4

[a]Corn was sampled at the V3 growth stage.
[b]Standard error of the mean.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Table 4.16. Effects of interseeding timing on legacy corn crop C and N content for each site in 2016 and 2018 combined over cover crop species.

Cover Crop	MSUAF 2016			MSUAF 2018			SVREC 2018		
	C	N	C:N	C	N	C:N	C	N	C:N
	%			%			%		
V1	-	-	-	44.68 a	1.83 ab	24.9 ab	43.59 a	3.57 a	12.4 a
V3	-	-	-	44.68 a	1.68 b	26.8 a	44.36 a	3.72 a	12.0 a
V5	44.80 a[b]	2.19 a	20.5 b	44.75 a	1.89 a	24.1 b	43.67 a	3.64 a	11.9 a
No cover	44.21 a	1.98 b	22.3 a	44.47 a	1.65 b	27.0 a	44.93 a	3.83 a	11.7 a
±SEM[a]	±0.17	±0.05	±0.6	±0.11	±0.12	±1.6	±0.30	±0.10	±0.4

[a]Standard error of the mean.

[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

Figure 4.01. Total inorganic N content for each site year for cover crop species combined across interseeding timings (a) and interseeding timings combined across cover crop species (b).

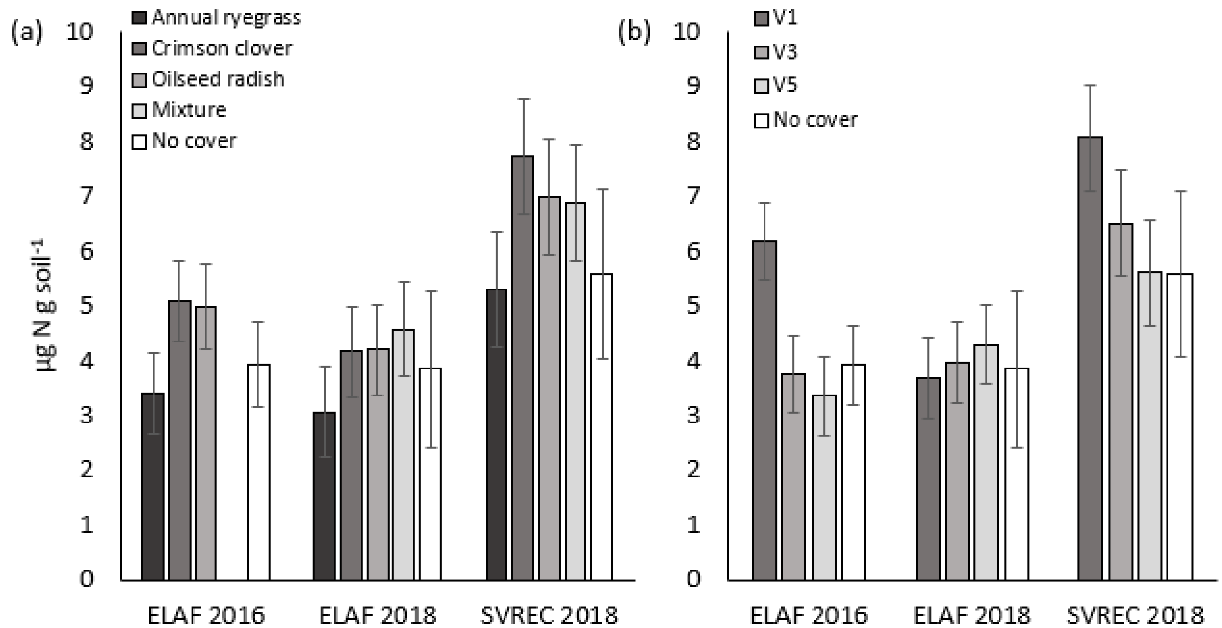

Figure 4.02. C:N for corn leaf tissue sampled at pollination[a] for each site year for cover crop species combined across interseeding timings (a) and interseeding timings combined across cover crop species (b). [a]Corn at SV was sampled at V3.

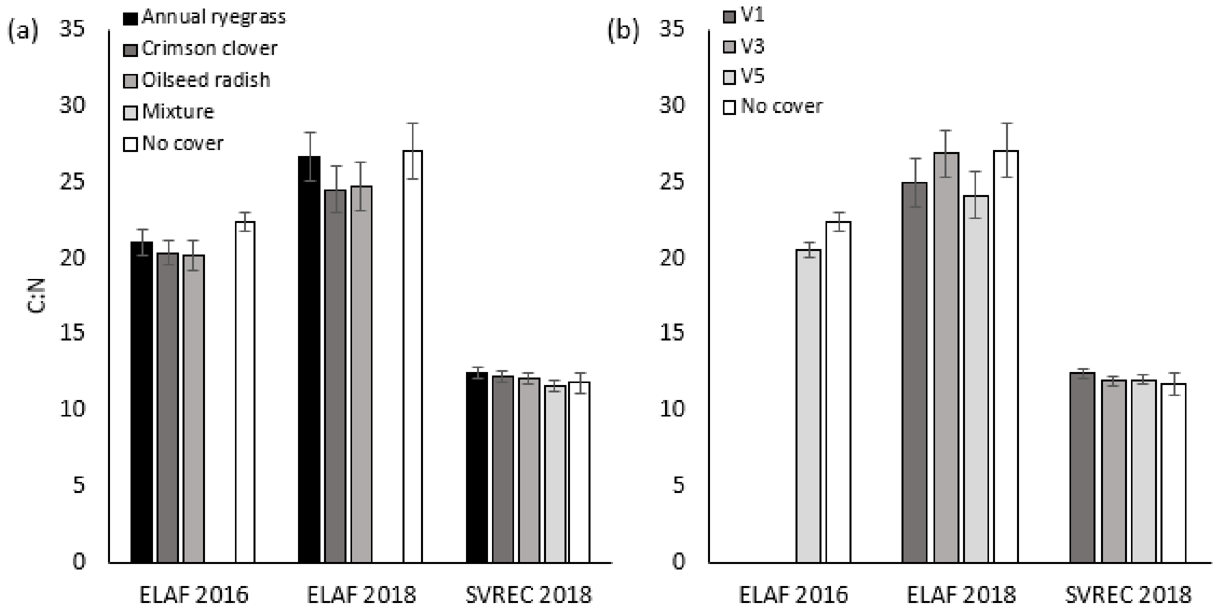

Figure 4.03. Factor analysis results using enzyme activities for the MSUAF 2016 (a) cover crop species; (b) interseeding timing, MSUAF 2018 (c) cover crop species; (d) interseeding timing, and SVREC 2018 (e) cover crop species; (f) interseeding timing; site years. Standardized scoring coefficients are given in the associated table. Points represent factor score means ± SE.

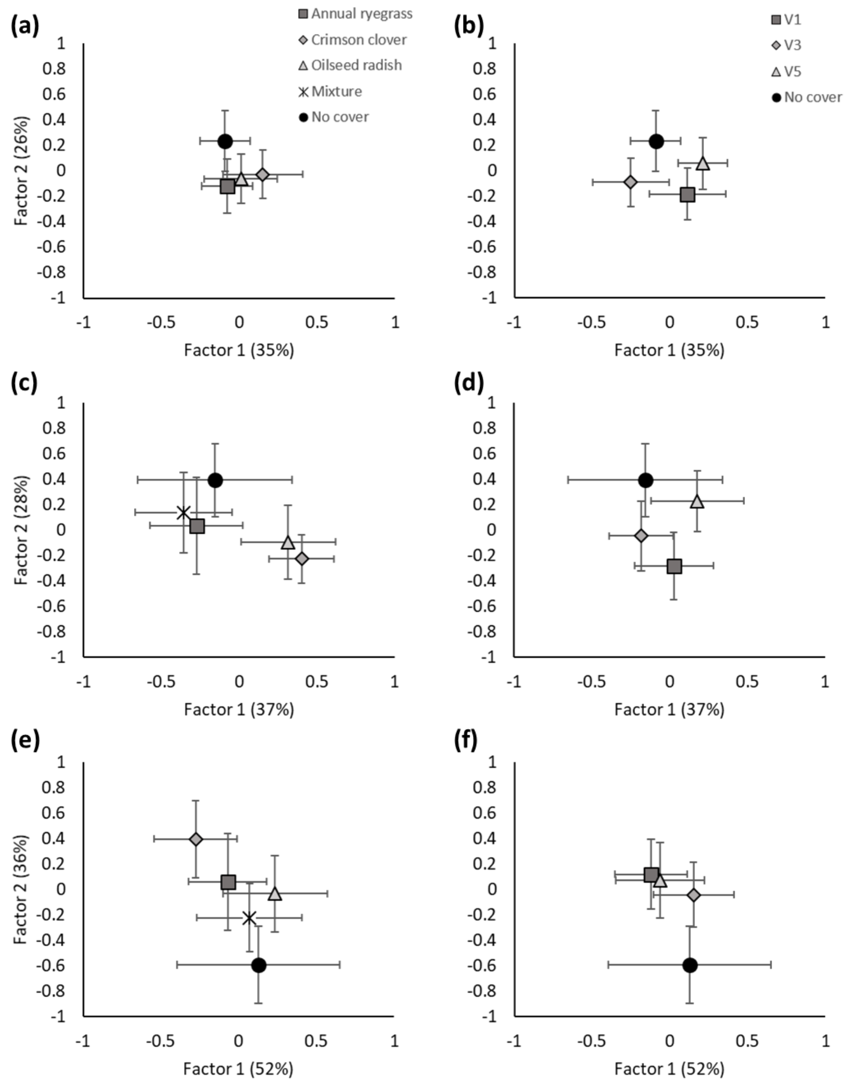

Figure 4.03 (*cont'd*).
Table of standardized scoring coefficients for each site year and enzyme activity.

	Site Year					
	MSUAF 2016		MSUAF 2018		SVREC 2018	
Enzyme	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
BG	0.300	-0.034	-0.103	0.274	-0.352	0.063
CBH	0.299	0.036	0.191	0.342	1.387	0.074
NAG	0.279	-0.090	-0.157	0.186	-0.194	-0.429
LAP	-0.039	0.160	-0.043	0.177	-0.159	-0.421
PHOS	0.240	0.153	-0.211	-0.051	0.097	2.429
PHEN	0.000	-0.066	0.107	-0.063	-0.358	-0.441
PER	0.015	0.837	0.379	0.008	0.541	-0.716
UREASE	0.087	-0.113	0.070	0.323	0.046	-0.066

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CHAPTER 5

INTERSEEDING COVER CROPS IN CORN: EFFECTS OF SEEDING RATE AND TIMING ON COVER CROP ESTABLISHMENT, BIOMASS, AND COMPETITIVENESS WITH CORN

Abstract

Interseeding cover crops in corn provides farmers with the option to include different cover crop species in corn-soybean rotations in the Upper Midwest. Most research has focused on species selection and interseeding timing, but optimal seeding rates for interseeding various cover crop species has not been reported; additionally, the performance of cover crops interseeded for a second consecutive year in the field has not been researched. An experiment was conducted in Michigan from 2017-2019 where annual ryegrass, crimson clover, oilseed radish, and a mixture of annual ryegrass and crimson clover were interseeded in V3 and V6 corn at three different seeding rates (0.5X, 1X, and 2X). In the year following interseeding (legacy year), corn was planted again, and cover crops were interseeded in the same plots as the previous year. Cover crop density and fall and spring biomass production were measured, as well as corn grain yield in both years. In the first year (initial year), sites receiving more rainfall had greater cover crop establishment and biomass production. Cover crop density and biomass production were usually higher when seeded at the 2X seeding rate compared with the 0.5X seeding rate when precipitation was adequate; in years with low precipitation, there were fewer differences. Spring biomass was usually similar for annual ryegrass and the mixture, but neither treatment provided winter annual weed suppression. Corn grain yield was not reduced by interseeded cover crops, regardless of species, seeding rate or timing. Farmers can broadcast interseed cover crops

at a wide range of seeding rates and timings without reducing corn grain yield. Seeding a mixture at similar rates used in this research could yield greater ecosystem benefits compared with a single species. Since costs increase with increasing seeding rates, farmers must balance their input costs with the potential for increased benefits from greater cover crop biomass production.

Introduction

Cover crops increase the diversity of crop rotations, which, in turn may improve cash crop productivity (Tiemann et al., 2015; McDaniel et al., 2014). Impacts of cover crops are seen in long term studies, including enhanced microbial community structure over a 31-year period (Mbuthia et al., 2015) and improved nitrogen use efficiency in corn over a seven-year period (Gabriel et al., 2016). In one seven-year study, cover crops improved soil water storage, potentially mitigating the impacts of rainfall variability in a time of climate change (Basche et al., 2016a). Corn and soybean yields are expected to decrease by 2060 in the Midwestern United States because of climate change; however, when cover crops are included no yield change is predicted (Basche et al., 2016b). The importance of cover crops to cash crop yield stability in the future is evident; the need for increased adoption of cover crops in the upper Midwest is imperative.

In a 2016 survey, farmers reported yield increases of 1.9% and 2.8% in corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.), respectively, with the addition of a cover crop (CTIC, 2017); however, cover crops are seeded on only 2% of United States farmland hectares (USDA-NASS, 2014). Farmers are hesitant to seed cover crops because of the cost, time, and labor involved, and the short growing season in the upper Midwest often limits the opportunity to establish a cover crop following corn grain harvest. Interseeding cover crops into corn provides another option for adding a cover crop in a corn rotation, increasing the potential for cover crop planting in future years.

Interseeding cover crops is not a new practice. In 1913, the USDA recommended interseeding crimson clover (*Trifolium incarnatum* L.) into corn, citing corn yield increases after many years of this practice (Westgate, 1913). Grower interest in interseeding cover crops has increased recently; grasses are the most popular interseeded species, followed by clovers, and then Brassicas (CTIC, 2017). Researchers report interseeding annual ryegrass (*Lolium multiflorum* Lam.) and crimson clover as single species and in mixtures (Abdin et al., 1998; Abdin et al., 1997; Belfry and Van Eerd, 2016; Curran et al., 2018; Grabber et al., 2014; Scott et al., 1987; Zhou et al., 2000); oilseed radish (*Raphanus sativus* L.) was interseeded as a single species in Pennsylvania and Ontario (Belfry and Van Eerd, 2016; Roth et al., 2015). In previous research, cover crops drill interseeded at V5 did not reduce corn yield in Pennsylvania (Curran et al., 2018); cover crops drill interseeded at V3-V4 in Ontario (Belfry and Van Eerd, 2016), V5 in Michigan (Baributsa et al. 2008) and V7 in Minnesota (Noland et al. 2018) did not reduce grain yield. Current guidelines from the United States Department of Agriculture Risk Management Agency for crop insurance when cover crops are interseeded is unclear; guidelines state that cover crops can be intercropped in corn only if they can be managed separately agronomically (RMA, 2019).

The Midwest Cover Crop Council provides recommendations for cover crop seeding rates in the Midwestern United States (MCCC, 2019); however, there is no information provided for rates when interseeding. Interseeding research has focused on the timing of interseeding, and effects on corn grain yield. There is limited information on how cover crop seeding rates influence establishment, biomass, and the ecosystem services provided by the cover crops.

Therefore, the objective of this research was to compare the establishment, biomass, and competitiveness of three cover crop species and one mixture when interseeded at three seeding rates in corn at the V3 and V6 growth stages in year 1 (initial year) and when seeded a second consecutive year in the same field (legacy year).

Materials and Methods

Experiments were initiated at the Michigan State University Agronomy Farm (MSUAF) in East Lansing, MI (42°42'38.64" N, 84°28'16.65" W) on an Aubbeenaubbee-Capac sandy loam in 2017 and a Conover loam in 2018, and at the Saginaw Valley Research and Extension Center (SVREC) in Richville, MI (42°17'59.45" N, 83°41'51.47" W) on a Tappan-Londo loam in 2017 and 2018. Soil organic matter at the MSUAF was 3.1 and 3.8% in 2017 and 2018, respectively, and 3.2 and 3.0% at SVREC in 2017 and 2018, respectively. The experimental design was a split-plot with four replications; cover crop species was the main plot and the combination of cover crop seeding rate and interseeding timing was the subplot. Plot size was 3 m wide (4 corn rows) and 12 m long. Cover crop species included annual ryegrass, oilseed radish, and crimson clover with NitroCoat® seed coating, and annual ryegrass + crimson clover in a 25:75 mixture by weight (La Crosse Seed LLC., La Crosse, WI). Interseeding timings were based on the corn growth stage measured by the leaf collar method (Abendroth et al., 2011) and included the V3 and V6 growth stages. Cover crops were interseeded at 0.5, 1, and 2 times the standard seeding rate. Standard seeding rates for single species were within ranges recommended by Sustainable Agriculture Research and Education (SARE) and were 17 kg ha^{-1} for annual ryegrass, 11 kg ha^{-1} for oilseed radish, 22 kg ha^{-1} of coated seed for crimson clover (Clark, 2007). The standard mixture seeding rate was 6 kg ha^{-1} and 17 kg ha^{-1} of annual ryegrass and crimson clover, respectively (Kramberger et al., 2014).

In the first year (initial year) at each MSUAF site, fields were chisel plowed in the fall prior to the experiment and soil finished in the spring using a Kongskilde soil finisher just prior to planting. Nitrogen as urea (CH_4N_2O) was broadcast prior to tillage and incorporated at a rate of 155 kg urea ha^{-1}, and an additional 32 kg ha^{-1} of N as urea and ammonium nitrate (NH_4NO_3), P as P_2O_5, and K as K_2O were applied in a 5 x 5-cm band as starter at planting. In the first year at each SVREC site, tillage included a disc ripper in the fall prior to the experiment and a triple K in the spring prior to planting. Nitrogen at 157 kg urea ha^{-1} was applied prior to planting. At each site, glyphosate (N-(phosphonomethyl)glycine)-resistant corn was planted in late April to mid-May using a four-row corn planter in 76-cm rows. Seeding depth was 3.8 cm at MSUAF and 5 cm at SVREC and the seeding rate in all site years was 79,000 seeds ha^{-1}. In the following year (legacy year) at each site location, the field was not tilled, and corn was planted using a four-row no-till corn planter. No nitrogen was applied at planting. At the V3 corn stage at MSUAF, N as urea was broadcast at 225 kg ha^{-1}. At the V3 corn stage at SVREC, N as 28% was injected between rows at 280 L ha^{-1}. Weeds were controlled the week prior to corn planting, and glyphosate (0.84 kg ae ha^{-1}) + AMS was applied when corn reached the V3 growth stage.

Cover crops were broadcast interseeded at the 0.5x, 1x, and 2x seeding rates at both the V3 and V6 corn growth stages using a hand-spreader between the first and fourth corn rows so that three interrow spaces were interseeded. Cover crop seeding dates were in May and June and depended on corn planting date and corn growth stage at each location in each year (Table 5.01). Glyphosate at 0.84 kg ae ha^{-1} was applied the day of each interseeding using a tractor-mounted, compressed air sprayer to control emerged weeds. Two control plots were included: a weed-free, no cover crop control to determine corn grain yield in the absence of competition from weeds and cover crops, and a no-glyphosate, no cover control to determine corn grain yield under weedy conditions. Overwintering cover crop density and biomass was measured in April of the following year, cover crops were then terminated with glyphosate, corn was no-till planted, and cover crops interseeded in the legacy year following the aforementioned methods with the same plot layout as the initial year.

In the initial and legacy years, photosynthetically active radiation (PAR) was measured between the second and third corn rows in each plot from the first interseeding date to the time of corn pollination using a SunScan Canopy Analysis System type SS1 (Delta T Devices Ltd., 2016). Daily rainfall data was acquired from weather stations located at MSUAF and SVREC as part of the Michigan Enviro-weather Network (MAWN, 2018).

Two, 0.25 m^2 quadrats were permanently marked between the second and third corn rows 14 days after interseeding (DAI). Cover crop emergence was measured 30 DAI in each quadrat. Fall cover crop density and aboveground cover crop biomass was harvested from the quadrats in October each year prior to corn harvest. For the cover crop mixture, individual species density was recorded, but biomass was not separated by species. Weeds were controlled using glyphosate prior to cover crop interseeding and using hand-weeding following interseeding. In April of the legacy year, overwintering cover crop and weed density and biomass were measured from two 0.25 m^2 quadrats placed adjacent to the previous quadrats between the second and third corn rows. Dry weights were recorded following oven-drying at 80°C for at least three days. Corn grain was harvested from the second and third corn rows using a plot combine; the weight of the harvested grain was recorded and adjusted to 15% moisture content.

Statistical Analyses

Cover crop emergence, density and biomass, weed density and biomass, and corn grain yield were analyzed using PROC MIXED in SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2012). All site years were analyzed separately. Data normality was examined by checking residual distribution; for density measurements, a Poisson distribution was considered; but results did not change compared with a normal distribution. Cover crop species, interseeding timing, seeding density and all interactions of the three were considered fixed effects, site year (when not significant) and replication nested within site year were considered random effects. Analyses were conducted to determine differences in cover crop emergence, density and biomass, winter annual weed density and biomass, and corn grain yield. Comparisons of least square means at $P \leq 0.05$ were made if F tests were significant ($P \leq 0.05$) using t tests conducted by the SAS pdmix800 macro (Saxton, 1998). Reported treatment means were significantly different at $P \leq 0.05$, unless otherwise noted.

Results and Discussion

Timing of Interseeding, Precipitation and PAR

Corn planting date in the initial year ranged from April 26 to May 15 across the four site-years (Table 5.01), and cover crop interseeding at the V3 growth stage occurred 18 to 30 days after corn planting. In the legacy year, corn was planted on June 1 at both sites, and cover crop interseeding at the V3 and V6 growth stages occurred 17 to 26 days after corn planting, respectively. Heat units, as well as precipitation, influenced corn growth stage. Growing degree days (GDD, base 10) from planting to V3 ranged from 146-224, and from V3 to V6 ranged from 69-194. There were more GDD from V3 to V6 in 2017 compared with 2018, likely due to greater precipitation and reduced corn stress. Cumulative precipitation from two weeks prior to the V3 interseeding timing to two weeks after the V6 interseeding timing (May 15 to July 15) were 12.8, 16.4, 10.3, and 7.2 cm for MSUAF 2017, SVREC 2017, MSUAF 2018, and SVREC 2018, respectively (Table 5.02). All site years were drier than the 30-year average (1981-2010) of 25 cm for May-July at Lansing, MI and 23 cm at Flint, MI, respectively (NOAA, 2019). A grower would not be able to base interseeding timing on GDD because soil moisture influenced corn development; a planned V3 interseeding ranged from 2.5-4 weeks after corn planting; a V6 interseeding was 5 to 8 weeks after planting.

Photosynthetically active radiation (PAR) beneath the corn canopy was measured two weeks following each interseeding (Table 5.03). PAR did not differ across the cover crop treatments, so measurements were combined within each site year. PAR beneath the corn canopy two weeks after V3 interseeding ranged from 24 to 81%; PAR measured two weeks after the V6 ranged from 9 to 32% (Table 5.03). In dry years, there was greater PAR penetrating the corn canopy at both the V3 and V6 interseeding timings as corn leaf area was reduced. Additional light penetrating the corn canopy following the V3 interseeding timing should be beneficial to cover crop establishment and early growth provided there is sufficient moisture compared with cover crops interseeded at the V6 corn stage.

Initial Year Cover Crop Emergence

The percentage of cover crop seed that emerged was not influenced by cover crop seeding rates as expected (data not shown). In the initial year, annual ryegrass, crimson clover, and oilseed radish emergence was 23, 7, and 22% in 2017 and 2, 2, and 4% in 2018, respectively, (data not shown). Previous research has shown that rainfall following interseeding is critical for cover crop establishment (Tribouillois et al, 2018; Constantin, 2015), and low precipitation in both initial years, especially in 2018, at both sites reduced cover crop seed germination and emergence (Table 5.02).

Initial Year Cover Crop Density

The density of all cover crop species was higher at the 2X seeding rate compared with 0.5X seeding rate in the initial year with the exception of oilseed radish at the MSUAF 2018 site 30 DAI (Table 5.04) and crimson clover at both sites in October 2018 (Table 4), suggesting that there was little intraspecific competition at these establishment densities. Previous interseeding research has not determined optimal seeding rates that limit intraspecific competition.

Annual ryegrass densities were higher when seeded at V3 compared with V6 at the SVREC 2017, MSUAF 2018, and SVREC 2018 sites but not the MSUAF 2017, when combined across seeding rates (Table 5.05). Oilseed radish densities were greater in the V3 interseeding timing (25 plants m^{-2}) compared with the V6 timing (10 plants m^{-2}) at the MSUAF 2017 site; crimson clover density was variable across site years (Table 5.05). Both annual ryegrass and crimson clover established when seeded in the mixture in all site years (Table 5.06). Cover crop density in October was higher for the V3 interseeding compared with the V6 interseeding only at the MSUAF sites (Table 5.06). Annual ryegrass and crimson clover densities in the mixture were similar 30 DAI, but by October annual ryegrass density was greater than crimson clover in 3 or 4 site years (Table 5.06). Total density of the mixture was highest for the 2X seeding rate in three of four site years (Table 5.06). The 2X mixture contained 12 and 34 kg ha^{-1} of annual ryegrass and crimson clover, respectively; 12 kg ha^{-1} is similar to the 1X seeding rate for annual ryegrass seeded as a single species.

It appears that establishment of cover crops following precipitation differed by species. For example, in 2017 and 2018 at SVREC, annual ryegrass had higher emergence at the V3 interseeding while crimson clover had higher emergence at the V6 interseeding when measured 30 DAI. By October, annual ryegrass density was similar in the V3 and V6 interseedings, but density of crimson clover remained higher in the V6 interseeding. Rainfall was much greater following the V6 compared with the V3 interseeding; this may be an indication that annual ryegrass is more tolerant of periods without rain compared with crimson clover and oilseed radish. Fatal germination of crimson clover in the V3 interseeding may have resulted from the extended period of no precipitation following a heavy rainfall event (Constantin et al., 2015). Within the mixture, the low grass seeding rate used in this experiment (1X = 6 kg ha^{-1}) successfully prevented annual ryegrass from dominating the mixture, allowing establishment of clover. Other researcher have found that reducing the seeding rate of grasses in mixtures allows for success of each species in the mixture (Murrell et al. 2017; Finney and Kaye, 2016; Ranells and Wagger, 1997).

Initial Year Cover Crop and Weed Biomass

Fall biomass typically mirrored cover crop density measured in October (Tables 5.04 and 5.05). Annual ryegrass produced greater fall biomass at the 2X seeding rate compared with the 0.5X seeding rate except for at the MSUAF 2018 site (Table 5.04). Crimson clover produced greater biomass at the 2X seeding rate compared with the 0.5X rate except for at the SVREC 2018 site year (Table 5.04). Oilseed radish biomass was more variable and produced greater biomass at the 2X seeding rate compared with the 1X and 0.5X rates at the SVREC 2017 site only (Table 5.04). Overall, each species and the mixture had increasing biomass production potential as seeding rate increased; however, there was greater variability in biomass production at the 2X seeding rate (Figure 5.01) because the higher density of cover crops provided the potential for greater biomass production, but this was not always the case. This was especially evident for oilseed radish, as it produced 0 to 4000 kg ha^{-1} of fall biomass when seeded at the 2X rate (Figure 5.01). Interseeding at V3 did not always increase fall biomass; annual ryegrass biomass was not greater when seeded at V3, oilseed radish biomass was higher when seeded at V3 compared with V6 at the MSUAF 2017 site year only, and crimson clover biomass was quite variable across site years (Table 5.05).

Overall, fall cover crop biomass in the initial year was higher in 2017 compared with 2018 likely due to increased rainfall in 2017 (Tables 5.04 and 5.05). All species had the potential to produce similar amounts of biomass in years with greater rainfall. Despite lower densities, crimson clover and oilseed radish had the potential to produce biomass similar to that of annual ryegrass (Tables 5.04 and 5.05). Annual ryegrass biomass was similar to what was reported in previous interseeding research: 250 kg ha^{-1} in the Mid-Atlantic (Curran et al., 2018) and 400 kg ha^{-1} in dry conditions in Quebec (Zhou et al., 2000). Biomass of oilseed radish was 1767 kg ha^{-1} when interseeded in sweet corn in Canada; crimson clover biomass in the same experiment was 507 kg ha^{-1} (Belfry and Van Eerd, 2016). The biomass for these cover crop species was higher compared with our research, suggesting sweet corn as a shorter season crop with less leaf area allows for greater light penetration below the corn canopy and increased biomass of interseeded cover crop species.

Oilseed radish did not overwinter in Michigan, and few crimson clover plants overwintered; spring biomass of crimson clover was much lower compared with annual ryegrass and the mixture of annual ryegrass and crimson clover (Table 5.07). Annual ryegrass and the mixture produced similar amounts of biomass in the spring at the MSUAF 2017, SVREC 2017, and MSUAF 2018 sites; at the SVREC 2018 site, annual ryegrass produced 69 kg ha^{-1} compared with 20 kg ha^{-1} for the mixture (Table 5.07). Since the mixture was able to produce similar biomass to annual ryegrass at most locations, it may be a viable option to enhance the ecosystem services that two species provide compared to a single species. There were no differences in spring biomass when comparing interseeding timings (Table 5.07); however, biomass in the 2X rate was higher compared with the 1X and 0.5X rates at the MSUAF 2017, MSUAF 2018, and SVREC 2018 sites (Table 5.07). This was driven by annual ryegrass, as its biomass was greater at the 2X seeding rate compared with the 1X and 0.5X rates, but this was not true for the mixture and crimson clover seeded as a single species (data not shown).

There were no differences in spring weed biomass in the cover crop treatments compared with the weed-free or weedy control plots (Table 5.07). Winter annual weed biomass was variable, and no differences were detected across cover crop species and seeding rates (Table 5.07). Common winter annual weed species at the MSUAF 2018 site included annual bluegrass (*Poa annua* L.), common chickweed (*Stellaria media* L. Vill.), purple deadnettle (*Lamium purpureum* L.), shepherd's purse (*Capsella bursa-pastoris* L. Medik), and dandelion (*Taraxacum officionale* F. H. Wigg.), and these species drove the high weed biomass at this location (Table 5.07); there were few winter annual weeds at SVREC. The research sites were not hand-weeded once corn reached the R1 reproductive stage, and winter annual weeds could have established in the fall after the corn canopy senesced or in the early spring. The only difference within the cover crop treatments was at the SVREC 2018 site where weed biomass was greater in the V6 interseeding timing plots (9 kg ha^{-1}) compared with the V3 interseeding timing (2 kg ha^{-1}) (Table 5.07). Greater cover crop biomass may be required to provide winter annual weed suppression.

One review of 46 previous studies showed that high cover crop biomass production was the most important factor contributing to weed suppression into the season, and that cover crops can suppress weeds in the following crop similarly to other weed control methods (Osipitan et al. 2018). In another a meta-analysis, Baraibar et al. (2018) reported a negative correlation for spring cover crop biomass and spring weed biomass. Additionally, grass species and mixtures containing grasses provided better weed suppression compared with legumes and Brassicas in the meta-analysis (Baraibar et al., 2018); however, in our research, higher biomass of annual ryegrass achieved by higher seeding rates did not significantly reduce weed biomass.

Legacy Year

Emergence of all cover crop species 30 DAI at both sites in the legacy year 2018 was low: 2, 2, and 4% for annual ryegrass, crimson clover, and oilseed radish, respectively (data not shown). At the MSUAF 2018 site, annual ryegrass and oilseed radish densities at the 2X seeding rate were 30 and 4 plants m^{-2} compared with 8 and 1 plants m^{-2} for the 0.5X seeding rate, respectively; at the SVREC 2018 site, crimson clover density at the 2X rate was 18 plants m^{-2} compared with 6 plants m^{-2} at the 0.5X rate (Table 5.08). At the MSUAF 2018 site, density of annual ryegrass and crimson clover was higher at the V6 compared with the V3 interseeding timing, whereas at the SVREC 2018 site, density of crimson clover and oilseed radish was higher at the V3 compared with the V6 interseeding (Table 5.09). When measured in October, annual ryegrass density at the MSUAF 2018 site was highest at the 2X seeding rate (Table 5.08), and crimson clover density at the SVREC 2018 site was highest at the V3 compared with the V6 interseeding (Table 5.09). In the mixture in the legacy year, annual ryegrass density 30 DAI was higher compared with crimson clover, and density of both species combined was higher in the

V6 compared with the V3 interseeding at the MSUAF 2018 site (Table 5.10). By October, annual ryegrass density within the mixture was greater than crimson clover density at MSUAF 2018 (Table 5.10). Also at MSUAF 2018, density was higher for the 2X and 1X seeding rates of the mixture compared with the 0.5X seeding rate (Table 5.10).

In the 2019 legacy year, density of annual ryegrass, crimson clover, and oilseed radish seeded at V3 at the 2X rate was higher compared with the 0.5X rate for all but annual ryegrass at SVREC (Table 5.08). Emergence at these site years was high due to 4.9 cm of rainfall in the two weeks following interseeding at MSUAF 2019 and 8.4 cm of rainfall at SVREC 2019 (Table 5.02). Rainfall following the V6 interseeding was much less compared with the V3, and emergence was reduced (data not shown). Earlier interseeding dates may be beneficial in capturing late spring and early summer precipitation as climate changes.

Cover crop biomass in the 2018 legacy year did not increase as seeding rate increased (Table 5.08); this result is similar to the initial year results, as cover crop density did not increase as seeding rate increased. Crimson clover and the mixture biomass were higher in the V3 compared with the V6 interseeding at the SVREC 2018 location (Table 5.09). There were few differences in cover crop or weed biomass in the spring of 2018 (Table 5.11). Low density and biomass were likely due to lack of precipitation in the 2018 legacy year at both sites and no-tillage. Corn at the legacy site years was planted directly into the initial year plots without tillage, so broadcast interseeded cover crops may have had reduced seed-to-soil contact.

Corn Grain Yield

A windstorm at the SVREC 2017 location caused severe stalk lodging, so corn was not harvested. Corn grain yield in the other three initial site years was reduced in the weedy plot compared with the weed free control (Table 5.12). In the legacy year, weeds did not reduce corn yields (Table 5.12); drought in the legacy year likely reduced the competitive effects of weeds and cover crops. Yield of corn in the cover crop treatments was equal to that of the weed free control when combined across all site years in both the initial and legacy years. These results support previous research where corn grain yield was not reduced by cover crops interseeded at V3 or later in corn in the Mid-Atlantic (Curran et al., 2018), Ontario (Belfry and Van Eerd, 2016), Michigan (Baributsa et al. 2008) and Minnesota (Noland et al. 2018).

Conclusions

The objective of this research was to compare the establishment, biomass, and competitiveness of three cover crop species and one mixture when interseeded at three seeding rates in corn at the V3 and V6 growth stages in year 1 (initial year) and in a consecutive year (legacy year). All three cover crop species and the mixture established when interseeded in grain corn at V3 and the V6 growth stages. Some site-years had higher densities of cover crop species than other site-years. Annual ryegrass and oilseed radish were able to establish in years of lower precipitation, while crimson clover often failed to establish. Precipitation prior to and following cover crop interseeding was an important factor in establishment. In the legacy year where cover crops were interseeded in no-till corn, poor establishment occurred in 2018 but not at the V3 interseeding in 2019 because of vast differences in precipitation. All cover crop species established following V3 interseeding in the 2019 legacy year, suggesting that crimson clover in an irrigated grain corn system may be a viable cover crop option. In rain fed systems, interseeded cover crop emergence may be increased in tilled compared with no-till fields when rainfall is at or below normal amounts. Additionally, cover crop success at the V3 and V6 interseeding timings is linked to timing of rainfall; so, either time may be suitable for interseeding dependent on weather conditions.

Increasing the seeding rate of a cover crop increases the cash inputs by the farmer. In our research, doubling the recommended seeding rate increased the biomass of annual ryegrass, oilseed radish and crimson clover, but the increase in biomass per plant for each species varied; additionally, the correlation of density to biomass was highest for annual ryegrass (r^2=0.51) compared with the other two species (Figure 5.02). However, even at twice the biomass, winter annual weeds were not suppressed by annual ryegrass or crimson clover. Increased carbon inputs, enhanced microbial communities, and enhanced nutrient scavenging and cycling for succeeding cash crops are ecosystem services that may benefit from a 2X seeding rate. If additional carbon is the desired ecosystem service from the cover crop, all three cover crops showed the potential to produce similar amounts of biomass, with oilseed radish producing the greatest fall biomass; seeding annual ryegrass at 33 kg ha^{-1} or oilseed radish at a minimum of 20 kg ha^{-1} would produce the most biomass. Previous research has shown that C:N of annual ryegrass, crimson clover, and oilseed radish are 32.5 (Kramberger et al., 2009), 16.4, and 20.4 kg ha^{-1} (Schomberg et al., 2006), respectively. Consecutive years of interseeding may enhance ecosystem services including changes in microbial community dynamics, nitrogen cycling, and formation of soil aggregates and organic matter. Farmers must balance desired ecosystem services with costs of interseeding when determining cover crop species and seeding rates.

APPENDIX

APPENDIX E

CHAPTER 5 TABLES AND FIGURES

Table 5.01. Corn planting and harvest dates and cover crop seeding dates for each site year. Growing degree days (GDD; base 10°C) between corn planting and the V3 interseeding, and GDD between the V3 and V6 interseedings are shown.

Site Year	Corn Planting	GDD	V3	GDD	V6	Corn Harvest
Initial Year						
MSUAF 2017	May 15	297	June 6	349	June 23	Oct. 13
MSUAF 2018	May 8	391	June 3	178	June 15	Oct. 26
SVREC 2017	Apr. 26	263	May 26	288	June 12	Oct. 12
SVREC 2018	May 9	404	June 5	241	June 18	Oct. 16
Legacy Year						
MSUAF 2018	June 1	307	June 18	108	June 25	Oct. 26
MSUAF 2019	May 24	165	June 16	160	July 1	-
SVREC 2018	June 1	321	June 19	122	June 27	Oct. 16
SVREC 2019	May 8	167	June 7	182	June 28	-

Table 5.02. Total precipitation one week before (1WB) interseeding, two weeks after (2WA) interseeding, for the interseeding period (IP; one week prior to V3 to 30 days after V6) at V3 and V6 for each site year in Initial Year and in the Legacy Year.

	V3		V6			
Site Year	1WB	2WA	1WB	2WA	IP	May-July
Initial			Precipitation (cm)			
MSUAF 2017	0.1	1.9	4.4	0.2	9.7	15
MSUAF 2018	2.8	1.4	0.8	0.8	6.8	19
SVREC 2017	2.6	0.8	<0.1	4.7	15.5	20
SVREC 2018	0.8	0.8	0.5	0.7	6.5	14
Legacy						
MSUAF 2018	1.8	3.0	2.7	0.4	9.5	19
MSUAF 2019	2.7	4.9	0.1	3.3	-	-
SVREC 2018	5.5	6.0	5.2	0.8	14.3	14
SVREC 2019	3.1	13.4	1.1	2.2	-	-

Table 5.03. Photosynthetically active radiation (PAR) measured at ground level below the corn canopy as a percent of total PAR measured above the corn canopy for each site year. Measurements were taken two weeks following each of the V3 and V6 interseeding timings.

Site Year	V3	V6
Initial	%	
MSUAF 2017	66	23
MSUAF 2018	-	13
SVREC 2017	81	32
SVREC 2018	24	9
Legacy		
MSUAF 2018	59	26
MSUAF 2019	47	-
SVREC 2018	65	22
SVREC 2019	46	-

Table 5.04. Annual ryegrass, crimson clover, and oilseed radish density measured at 30 DAI and October, and biomass measured in October for each initial year site for each seeding rate (SR) combined over interseeding timings.

		MSUAF 2017			SVREC 2017			MSUAF 2018			SVREC 2018		
Cover crop	SR	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.
		plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}
	0.5x	94 c[a]	141 b[a]	118 b	124 b	147 b	159 b	9 b	17 b	85 a	5 b	8 b	11 b
Annual ryegrass	1x	143 b	211 ab	213 ab	267 a	198 b	189 b	9 b	28 ab	46 a	34 ab	13 b	12 b
	2x	249 a	263 a	326 a	330 a	336 a	355 a	28 a	37 a	165 a	56 a	31 a	41 a
±SEM		±21	±26	±56	±35	±33	±47	±6	±7	±51	±11	±5	±10
	0.5x	26 b	20 c	101 b	18 c	19 c	44 b	4 b	3 a	68 b	4 b	1 a	1 a
Crimson clover	1x	35 b	44 b	216 a	56 b	46 b	89 ab	9 b	5 a	83 b	25 a	5 a	8 a
	2x	75 a	70 a	295 a	95 a	75 a	102 a	21 a	9 a	301 a	27 a	8 a	11 a
±SEM		±6	±7	±39	±8	±6	±16	±3	±3	±55	±5	±3	±5
	0.5x	9 b	8 b	277 a	9 b	9 b	67 b	2 a	1 b	21 a	1 b	0 b	0 a
Oilseed radish	1x	19 ab	15 ab	431 a	28 ab	18 ab	70 b	3 a	2 b	132 a	5 ab	<1 ab	14 a
	2x	23 a	22 a	463 a	38 a	38 a	181 a	7 a	4 a	258 a	6 a	1 a	3 a
±SEM		±4	±4	±90	±10	±8	±32	±2	±1	±147	±2	±0.4	±6
	0.5x	-	-	114 b	-	-	100 b	-	-	4 b	-	-	10 a
Mixture	1x	-	-	168 b	-	-	150 b	-	-	14 ab	-	-	34 a
	2x	-	-	290 a	-	-	266 a	-	-	55 a	-	-	42 a
±SEM		-	-	±30	-	-	±31	-	-	±16	-	-	±12

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b] Standard error of mean for LSD comparisons.

Table 5.05. Annual ryegrass, crimson clover, and oilseed radish density measured at 30 DAI and October, and biomass measured in October for each initial year site for each interseeding timing (IT) combined over seeding rates.

		MSUAF 2017			SVREC 2017			MSUAF 2018			SVREC 2018		
Cover crop	IT	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.
		plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}
Annual ryegrass	V3	168 a[a]	208 a[a]	216 a	299 a	225 a	214 a	26 a	28 a	148 a	48 a	18 a	27 a
	V6	156 a	201 a	222 a	182 b	228 a	254 a	4 b	27 a	49 a	16 b	16 a	16 a
±SEM[b]		±19	±22	±45	±28	±28	±39	±5	±7	±45	±10	±4	±8
Crimson clover	V3	55 a	54 a	300 a	33 b	20 b	50 b	16 a	8 a	279 a	13 a	3 a	5 a
	V6	35 b	35 b	107 b	81 a	73 a	107 a	6 b	3 a	22 b	24 a	6 a	8 a
±SEM		±5	±6	±36	±7	±5	±13	±3	±2	±46	±5	±2	±4
Oilseed radish	V3	25 a	21 a	649 a	18 a	16 a	82 a	5 a	3 a	273 a	4 a	<1 a	4 a
	V6	10 b	9 b	131 b	31 a	28 a	130 a	3 a	1 a	1 a	4 a	1 a	8 a
±SEM		±3	±3	±74	±9	±6	±26	±1	±1	±121	±1	±<1	±5
Mixture	V3	-	-	299 a	-	-	156 a	-	-	39 a	-	-	35 a
	V6	-	-	83 b	-	-	187 a	-	-	11 a	-	-	21 a
±SEM		-	-	±26	-	-	±28	-	-	±13	-	-	±9

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b] Standard error of mean for LSD comparisons.

Table 5.06. Annual ryegrass and crimson clover density in the mixture measured at 30 DAI and in October prior to corn harvest for each initial year site for each seeding rate.

	Site Year							
Species	MSUAF 2017		SVREC 2017		MSUAF 2018		SVREC 2018	
	30DAI	Oct.	30DAI	Oct.	30DAI	Oct.	30DAI	Oct.
	plants m^{-2}							
Annual ryegrass	72 a[a]	85 a[a]	125 a	137 a	11 a	13 a	11 a	4 a
Crimson clover	49 a	34 b	66 a	39 b	5 a	1 b	17 a	4 a
±SEM	±6	±8	±15	±10	±2	±2	±3	±1
Interseeding Timing								
V3	70 a	73 a	82 a	78 a	8 a	9 a	16 a	4 a
V6	51 b	46 b	109 a	98 a	7 a	4 b	12 a	4 a
±SEM	±6	±8	±15	±10	±2	±2	±3	±1
Seeding Rate								
0.5X	30 b	25 b	36 b	33 c	1 b	5 a	3 c	1 b
1X	46 b	47 b	80 b	71 b	5 b	5 a	15 b	3 b
2X	106 a	106 a	171 a	161 a	16 a	9 a	24 a	7 a
±SEM[b]	±7	±9	±17	±12	±2	±2	±3	±1

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 5.07. Spring cover crop (cover) and winter annual weed (weed) biomass for each species, interseeding timing, and seeding rate measured in April for each initial year site.

	Site Year							
	MSUAF 2017		SVREC 2017		MSUAF 2018		SVREC 2018	
Cover crop species	Cover	Weed	Cover	Weed	Cover	Weed	Cover	Weed
	kg ha^{-1}							
Annual ryegrass	236 a[a]	41 a[a]	262 a	1 a	45 a	209 a	69 a	6 a
Crimson clover	4 b	63 a	12 b	16 a	1 b	239 a	4 b	8 a
Oilseed radish	-	61 a	-	9 a	-	266 a	-	5 a
Mixture	181 a	51 a	221 a	4 a	36 a	233 a	20 b	4 a
±SEM	±56	±20	±42	±5	±9	±74	±9	±4
Interseeding Timing								
V3	158 a	44 a	164 a	10 a	28 a	223 a	37 a	2 b
V6	122 a	65 a	166 a	5 a	27 a	250 a	24 a	9 a
±SEM	±43	±13	±39	±3	±7 b	±71	±7	±3
Seeding Rate								
0.5X	91 b	55 a	136 a	7 a	16 b	209 a	17 b	8 a
1X	125 b	42 a	191 a	10 a	21 b	274 a	14 b	2 a
2X	205 a	66 a	168 a	6 a	46 a	227 a	61 a	6 a
±SEM[b]	±45	±15	±42	±4	±8	±73	±9	±3
Weedy	-	33	-	16	-	64	-	5
Weed-free	-	72	-	15	-	176	-	7

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 5.08. Annual ryegrass, crimson clover, and oilseed radish density measured at 30 DAI and in October, and biomass measured in October for each legacy year site for each seeding rate (SR).

		MSUAF 2018			MSUAF 2019[c]			SVREC 2018			SVREC 2019		
Cover crop species	SR	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.
		plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}	kg ha^{-1}	
	0.5x	8 b	20 b[a]	33 a	56 b	-	-	4 a	3 a	7 a	92 a	-	-
Annual ryegrass	1x	15 ab	32 ab	55 a	84 b	-	-	5 a	4 a	11 a	140 a	-	-
	2x	30 a	54 a	79 a	224 a	-	-	9 a	8 a	15 a	164 a	-	-
±SEM		±5	±9	±20	±20	-	-	±5	±2	±6	±28	-	-
	0.5x	1 a	1 a	2 a	16 b	-	-	6 b	2 a	23 a	32 b	-	-
Crimson clover	1x	2 a	2 a	17 a	20 b	-	-	9 b	9 a	52 a	56 ab	-	-
	2x	4 a	2 a	7 a	40 a	-	-	18 a	9 a	57 a	100 a	-	-
±SEM		±1	±1	±9	±4	-	-	±3	±4	±15	±12	-	-
	0.5x	1 b	1 a	74 a	4 b	-	-	3 a	<1 a	1 a	8 b	-	-
Oilseed radish	1x	2 ab	2 a	41 a	16 ab	-	-	5 a	1 a	8 a	8 b	-	-
	2x	4 a	4 a	89 a	28 a	-	-	4 a	2 a	59 a	20 a	-	-
±SEM		±1	±1	±37	±4	-	-	±1	±1	±32	±4	-	-
	0.5x	-	-	9 a	-	-	-	-	-	28 a	-	-	-
Mixture	1x	-	-	25 a	-	-	-	-	-	98 a	-	-	-
	2x	-	-	42 a	-	-	-	-	-	85 a	-	-	-
±SEM		-	-	±13	-	-	-	-	-	±22	-	-	-

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.
[c]2019 October data were not yet collected.

Table 5.09. Annual ryegrass, crimson clover, and oilseed radish density measured at 30 DAI and in October, and biomass measured in October for each legacy year site for each interseeding timing (IT) averaged over seeding rates.

		MSUAF 2018			MSUAF 2019[c]			SVREC 2018			SVREC 2019		
Cover crop species	IT	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.	30DAI	Oct.	Oct.
		plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}	plants m^{-2}		kg ha^{-1}
Annual ryegrass	V3	3 b[a]	30 a[a]	62 a	-	-	-	10 a	4 a	9 a	-	-	-
	V6	32 a	40 a	49 a	-	-	-	1 a	6 a	11 a	-	-	-
±SEM		±4	±8	±17	-	-	-	±4	±2	±5	-	-	-
Crimson clover	V3	1 b	1 a	2 a	-	-	-	22 a	12 a	85 a	-	-	-
	V6	4 a	3 a	16 a	-	-	-	<1 b	1 b	3 b	-	-	-
±SEM		±1	±1	±8	-	-	-	±2	±3	±12	-	-	-
Oilseed radish	V3	2 a	2 a	52 a	-	-	-	8 a	2 a	45 a	-	-	-
	V6	3 a	3 a	84 a	-	-	-	<1 b	<1 a	0 a	-	-	-
±SEM		±1	±1	±31	-	-	-	±1	±1	±26	-	-	-
Mixture	V3	-	-	31 a	-	-	-	-	-	116 a	-	-	-
	V6	-	-	19 a	-	-	-	-	-	25 b	-	-	-
±SEM[b]		-	-	±10	-	-	-	-	-	±18	-	-	-

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.
[c]2019 October data were not yet collected.

Table 5.10. Mixture emergence for each cover crop species, interseeding timing, and seeding rate measured at 30 DAI and in October prior to corn harvest in the Legacy Year.

	Site Year					
	30 DAI				October	
Species	MSUAF 2018	SVREC 2018	MSUAF 2019[c]	SVREC 2019	MSUAF 2018	SVREC 2018
	plants m^{-2}					
Annual ryegrass	8 a[a]	1 a	36 a	44 a	9 a	2 a
Crimson clover	1 b	4 a	16 b	40 a	1 b	4 a
±SEM	±2	±1	±4	±4	±2	±1
Interseeding Timing						
V3	2 b	5 a	-	-	6 a	3 a
V6	7 a	1 a	-	-	4 a	4 a
±SEM	±2	±1	-	-	±2	±1
Seeding Rate						
0.5X	1 a	2 a	8 c	28 b	1 b	2 a
1X	5 a	4 a	28 b	36 b	7 a	5 a
2X	7 a	3 a	48 a	56 a	7 a	4 a
±SEM[b]	±2	±1	±4	±8	±2	±1

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.
[c]2019 October data were not yet collected.

Table 5.11. Spring cover crop and weed biomass for each species, interseeding timing, and seeding rate for each Legacy Year site.

	Site Year			
	MSUAF 2018		SVREC 2018	
Species	Cover	Weed	Cover	Weed
	kg ha^{-1}			
Annual ryegrass	47 a	97 a[a]	96 a	6 a
Crimson clover	6 a	189 a	7 b	3 a
Oilseed radish	-	143 a	-	5 a
Mixture	52 a	122 a	63 ab	15 a
±SEM	±19	±50	±18	±6
Interseeding Timing				
V3	30 a	131 a	36 a	7 a
V6	40 a	144 a	75 a	8 a
±SEM	±14	±15	±15	±5
Seeding Rate				
0.5X	31 a	172 a	57 a	4 a
1X	26 a	129 a	56 a	10 a
2X	48 a	113 a	53 a	8 a
±SEM[b]	±15	±32	±18	±5
Weed-Free	-	111	-	19

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 5.12. Corn grain yield for each year combined over site years[a] 1) for each cover crop species combined over interseeding timings and seeding rates, 2) for each interseeding timing combined over cover crop species and seeding rates, and 3) for each seeding rate combined over cover crop species and interseeding timings.

Cover Crop Treatment	Year One	Legacy Year
	------Corn grain yield (Mg ha^{-1})------	
annual ryegrass	11.1 a	8.3 a
crimson clover	11.6 a	8.2 a
oilseed radish	11.4 a	8.6 a
mixture	11.3 a	8.1 a
Interseeding Timing		
	------Corn grain yield (Mg ha^{-1})------	
V3	11.3 a	8.1 a
V6	11.4 a	8.5 a
Seeding Rate		
	------Corn grain yield (Mg ha^{-1})------	
0.5x	11.4 a	8.4 a
1x	11.5 a	8.3 a
2x	11.2 a	8.1 a
weedy[b]	9.0*	8.3
weed-free[b]	11.6	8.4

[a] SVREC 2017 was not included due to severe lodging caused by a wind storm.

[b] Analyzed separately and compared with each cover crop by interseeding timing combination; Values with an asterisk are significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[c] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

* Indicates a reduction in corn grain yield compared with the combination of species, interseeding timing, and seeding rate at $\alpha = 0.05$.

Figure 5.01. Range of annual ryegrass (a), crimson clover (b), oilseed radish (c), and mixture (d) biomass at each seeding rate combined over all initial year sites.

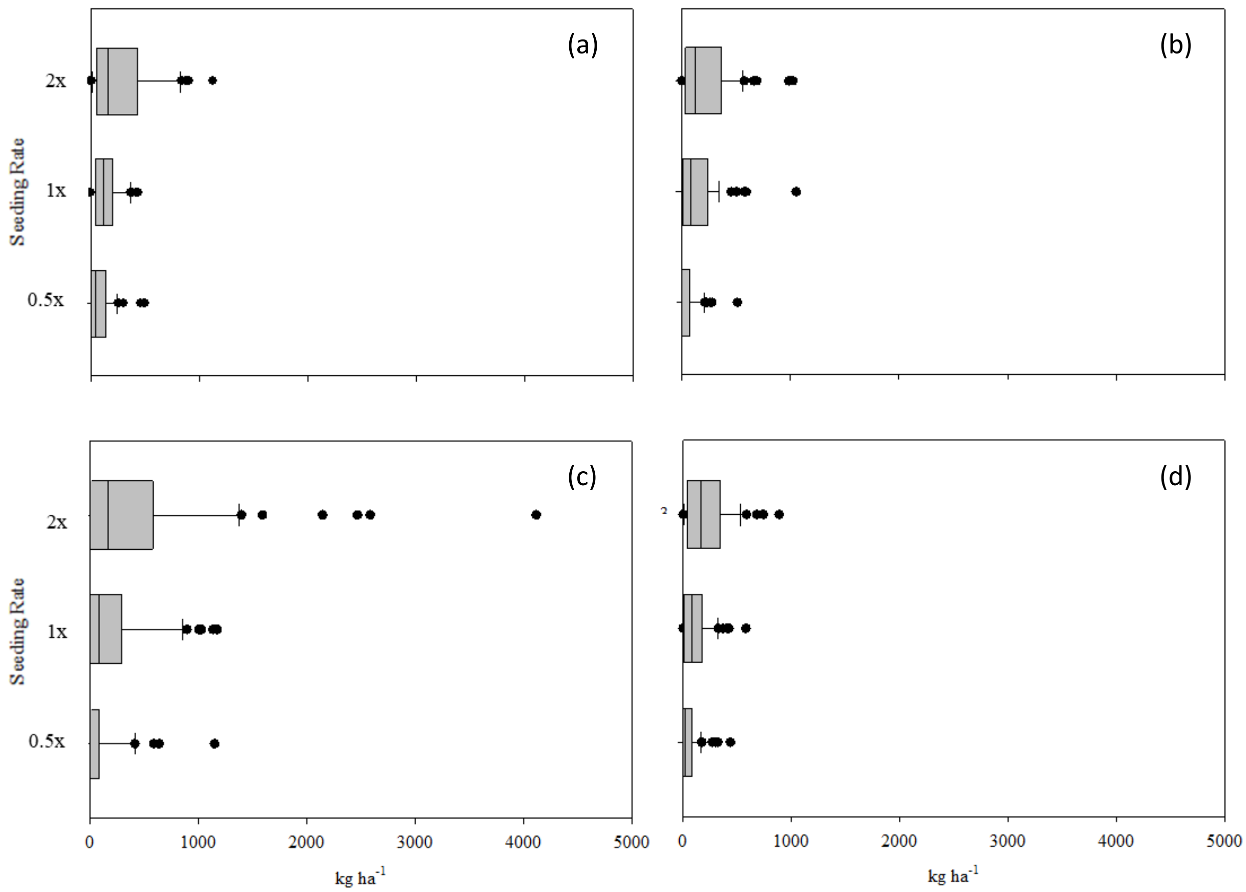
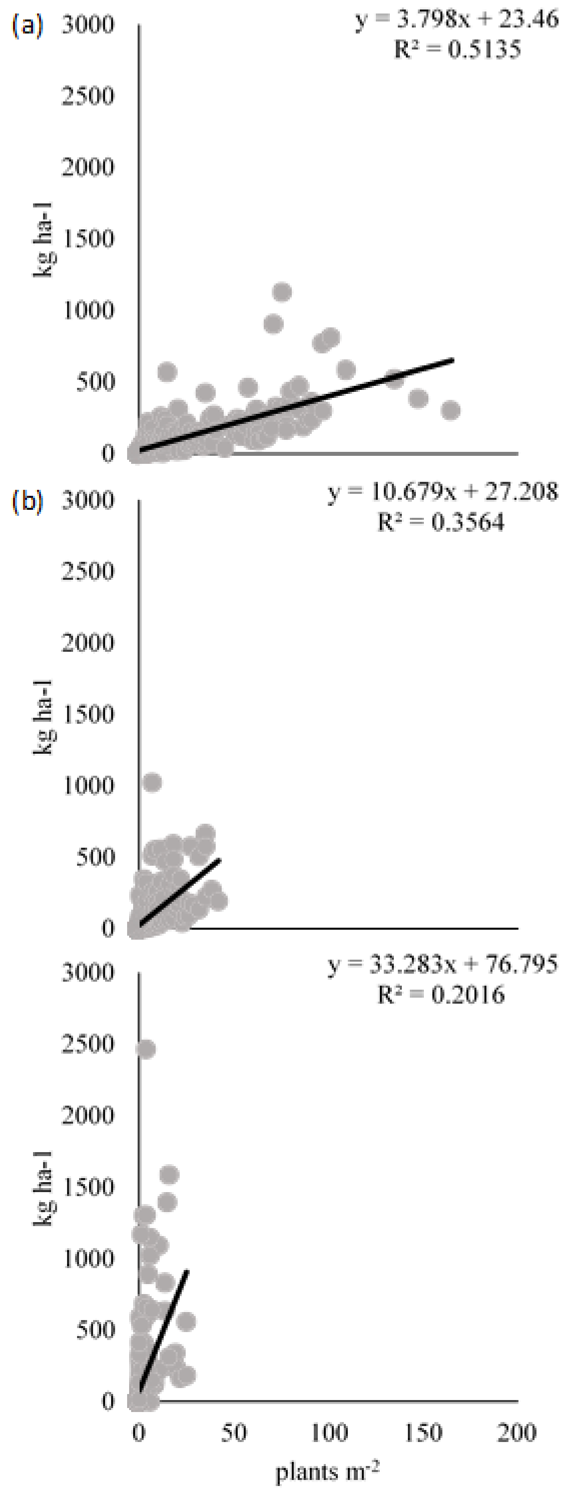


Figure 5.02. Relationship between annual ryegrass (a), crimson clover (b), and oilseed radish (c) density and biomass produced in October.



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CHAPTER 6

ASSESSING INTERSEEDED COVER CROP ESTABLISHMENT AND COMPETITIVENESS IN MAIZE USING REMOTE SENSING

Abstract

Interseeding cover crops in corn at the early vegetative stages gives farmers an option to add cover crops to corn and soybean rotations where seasonal constraints limit establishment following cash crop harvest. Previous interseeding has not evaluated cover crop competitiveness with corn when interseeding at various seeding rates; furthermore, remote sensing has not been utilized to monitor cover crop establishment and corn health in interseeded systems. The objectives of this research were to evaluate the establishment and competitiveness of cover crops interseeded in corn at varying seeding rates using remotely sensed canopy temperature and multispectral imagery. In 2017 and 2018 at East Lansing and Richville, MI, annual ryegrass, crimson clover, oilseed radish, and a mixture of annual ryegrass and crimson clover were interseeded in V3 and V6 corn at three different seeding rates. Canopy temperature was remotely measured using fixed wing aircraft multiple times throughout the season. Multispectral imagery was measured remotely using an UAV three times throughout the season, and two vegetation indices, normalized difference vegetation index (NDVI) and normalized difference red-edge (NDRE), were calculated. The ability of remote sensing to detect cover crops was variable; remote sensing was sometimes able to detect cover crops in V3 interseeded plots prior to the V6 interseeding timing. Following corn canopy closure, there were few differences in canopy temperature, NDVI, and NDRE. Cover crops did not enhance or reduce corn grain yield compared to the no cover control treatment, providing ground truth support of the remote sensing

results. Where interseeded cover crops are more competitive with corn, or where farm fields have had multiple years of cover crops compared with no cover crop control areas, remote sensing may be a useful tool to detect cover crop competition with corn or the soil health benefits of cover crops that enhance corn growth and development.

Introduction

Seeding cover crops is difficult in a maize (*Zea mays* L.)–soybean (*Glycine max* L. Merr.) rotation in the northern United States. Cover crops can be seeded following winter wheat harvest in mid-summer, but winter cereals are the only option for a cover crop seeding after soybean or corn harvest in the fall (Baker and Griffis, 2009). Interseeding cover crops in maize during the early vegetative growth stages is an opportunity to establish a grass or broadleaf cover crop and add rotational diversity to improve overall system productivity (Tiemann et al. 2015; McDaniel et al., 2014).

Researchers have shown that cover crops can be interseeded in maize without reducing grain yield. Annual ryegrass (*Lolium multiflorum* Lam.) and red clover (*Trifolium pretense* L.) interseeded after the V2 maize growth stage (Abendroth, 2011) did not reduce grain yield in Pennsylvania, Maryland, and New York (Curran et al. 2018). Red clover interseeded in maize at the V5 to V7 growth stages did not reduce grain yield in Michigan (Baributsa et al. 2008), and Noland et al. (2018) found that cover crops interseeded with a drill, broadcast, and broadcast + incorporation at the V7 growth stage of maize did not reduce grain yield in Minnesota.

The mechanisms by which cover crops potentially compete with cash crops have not been the focus of previous published small plot research. In farmer’s fields, where soil type and topography vary, cover crops could compete with maize for water and nutrients. Grain yield of maize grown in a no-till rotation with soybean and canola in years with near average rainfall was 10.3 Mg ha^{-1} and only 4.1 Mg ha^{-1} in a drought year in Michigan; evapotranspiration (ET) of corn in average rainfall years was 469 mm but was 20% lower in drought years (Hussain et al. 2019). In intercropping experiments, sole maize usually yielded more than maize intercropped with soybean (Ren et al. 2015). However, where pea (*Pisum sativum* L.) (Chen et al., 2018) and wheat (*Triticum aestivum* L.) (Yang et al. 2011) were intercropped with maize, water use efficiency increased, and total crop yields increased compared with sole crops.

Remote sensing is an important tool for detecting crop stress across small-plot and field scale cropping systems. Thermal and multispectral imaging by unmanned aerial vehicles (UAV) and fixed-wing imagery allows researchers to monitor crop growth throughout the growing season. Normalized difference vegetation index (NDVI) (Tucker, 1979), the difference between near-infrared light reflected by leaves and red light which is highly absorbed by leaves, is correlated with photosynthetic activity (Maestrini and Basso, 2018). Normalized difference red-edge replaces the red band in the NDVI calculation and indicates the chlorophyll and nitrogen content of the cash crop (Fitzgerald et al., 2006). Measuring canopy temperature provides an estimate of plant transpiration, an indicator of soil water availability and photosynthetic rate (Maestrini and Basso, 2018). Remote sensing in interseeded systems may provide insight into how cover crops influence ET, maize growth and development, and water and nutrient availability throughout the growing season. The objectives of our research were to: a) determine if remote sensing could detect cover crop presence in maize; and b) determine if cover crop species or interseeding timing influenced ET and maize response to cover crops.

Materials and Methods

Experiments were initiated at the Michigan State University Agronomy Farm (MSUAF) in East Lansing, MI (42°42'38.64" N, 84°28'16.65" W) on an Aubbeenaubbee-Capac sandy loam in 2017 and a Conover loam in 2018, and at the Saginaw Valley Research and Extension Center (SVREC) in Richville, MI (42°17'59.45" N, 83°41'51.47" W) on a Tappan-Londo loam in 2017 and 2018. Soil organic matter was 3.1 and 3.8% at MSUAF in 2017 and 2018, respectively, and 3.2 and 3.0% at SVREC in 2017 and 2018, respectively. The experimental design was a split-plot with four replications; cover crop species was the main plot and the combination of cover crop seeding rate and interseeding timing was the subplot. Plot size was 3 m wide (4 maize rows) and 12 m long.

At each MSUAF site year, fields were chisel plowed in the fall prior to the experiment and soil finished in the spring just prior to planting. Nitrogen as urea (CH_4N_2O) was broadcast prior to tillage and incorporated at a rate of 155 kg urea ha^{-1}, and an additional 32 kg ha^{-1} of N as urea and ammonium nitrate (NH_4NO_3), P as P_2O_5, and K as K_2O were applied in a 5 x 5-cm band as starter at planting. At each SVREC site year, tillage included a disc ripper in the fall prior to the experiment and a triple K in the spring prior to planting. Nitrogen at 155 kg urea ha^{-1} was applied prior to planting. At each site year, glyphosate (N-(phosphonomethyl)glycine)-resistant maize was planted in late April to mid-May using a four-row planter in 76-cm rows (Table 6.01). Seeding depth was 3.8 cm at MSUAF and 5 cm at SVREC and the seeding rate in all site years was 79,000 seeds ha^{-1}. Weeds were controlled the week prior to maize planting and when maize reached the V3 and V6 (V6 plots only) growth stages (Abendroth et al., 2011) with a glyphosate (0.84 kg ae ha^{-1}) + AMS application.

Cover crop species included annual ryegrass, oilseed radish, and crimson clover with NitroCoat® seed coating, and annual ryegrass + crimson clover in a 25:75 mixture by weight (La Crosse Seed LLC., La Crosse, WI). Cover crops were interseeded between the first and fourth maize rows using a hand spreader at the V3 and the V6 growth stages (Abendroth et al., 2011) following the glyphosate application. Standard seeding rates for single species fell within ranges recommended by the Sustainable Agriculture Research and Education and were 17 kg ha^{-1} for annual ryegrass, 11 kg ha^{-1} for oilseed radish, 22 kg ha^{-1} of coated seed for crimson clover (Clark, 2007). The standard mixture seeding rate was 6 kg ha^{-1} and 17 kg ha^{-1} of annual ryegrass and crimson clover, respectively (Kramberger et al., 2014). Cover crops were broadcast interseeded at the 0.5x, 1x, and 2x seeding rates. Cover crop seeding dates were in May and June and depended on maize planting date and growth stage at each location (Table 6.01). Two control plots were included that were not interseeded with cover crops: one weed-free plot and one weedy plot where weeds were not controlled.

A commercial airborne image company, Airscout (Monee, IL) flew multiple times from May through October each year (Table 6.02) and collected plant surface temperature. Additionally, plot reflectance using a multispectral, UAV-mounted sensor was measured three times during the growing season from May to July (Table 6.03). This reflectance data was used to calculate two vegetation indices: NDVI (1) and NDRE (2) using the following equations:

$$NDVI = \frac{NIR_{780} - RED_{660}}{NIR_{780} + RED_{660}} \quad (1)$$

$$NDRE = \frac{790\ nm - 720\ nm}{790\ nm + 720\ nm} \quad (2)$$

Average plot temperature, NDVI, and NDRE were determined for each plot at each flyover time.

Statistical Analyses

Data were analyzed in SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2012). An initial analysis was conducted using the MIXED procedure to determine the effects of the independent variables cover crop species, interseeding timing, seeding density, time of measurement, and all interactions on the dependent variables plot temperature, NDVI, and NDRE. Time of measurement was considered a repeated measure for each independent variable and a compound symmetry covariance structure was used. Comparisons of least square means at $P \leq 0.05$ were made if F tests were significant ($P \leq 0.05$) using t tests conducted by the SAS pdmix800 macro (Saxton, 1998). Additionally, contrasts were used to determine differences in temperature, NDVI, and NDRE comparing weedy control plots and plots interseeded with cover crops. Finally, the REG procedure evaluated both cover crop biomass and maize grain yield correlations with canopy temperature, NDVI, and NDRE. Slope was determined to be different from zero when the model was significant at $P \leq 0.05$. The coefficient of determination (R^2) determined the proportion of variance in cover crop biomass and grain yield explained by temperature, NDVI, and NDRE.

Results and Discussion

Interseeded Cover Crop Effects on Canopy Temperature

Canopy temperature differed across sampling dates (Table 6.04). Overall, canopy temperature was a reflection of air temperature and rainfall prior to the measurement. Warm days, or consecutive warm days resulted in higher canopy temperatures, and cool temperatures lowered canopy temperatures. Rainfall prior to a measurement also lowered canopy temperatures in some instances (Figure 6.01 (a-c)). At the SVREC 2018 site year, canopy temperature was higher in weed-free plots (23.8°C) compared with all other plots (23.4°C) when measured on 18 July; when measured on 29 July, weed-free plot temperatures were higher (23.7°C) compared with all other plots (23.5°C) (Table 6.07). There were no differences in canopy temperature for the other site years (Tables 6.05-6.07). Since canopy temperature is strongly influenced by air temperature, canopy closure, and evapotranspiration (Sauer et al. 2007), our results were not surprising. Generally, canopy temperatures were higher when daytime temperatures were higher, following consecutive days of high daytime temperatures, or following multiple days without precipitation. Canopy temperatures were lower when air temperatures were lower or following a rainfall event because cooling occurred from increased evapotranspiration (Mahan et al. 2012) (Figure 6.01 (a-c)). At the SVREC 2018 site year, canopy temperatures were usually higher early in the season compared with later in the season. Since there was little rainfall from late May to mid-July, temperatures were likely influenced by differences in soil and plant temperature: as canopy closure increased during this time; less bare soil lowered canopy temperatures. The differences in the weed-free plots in July at the SVREC 2018 location were likely due to bare soil under the corn canopy compared with plots interseeded with cover crops; however, this effect was not observed in other site years.

Interseeded Cover Crop Effects on NDVI and NDRE

NDVI and NDRE increased with later measurement dates in most site years (Table 6.08). One exception to this was at the MSUAF 2018 site, where NDVI and NDRE were higher at the July 5 measurement compared with the July 20 measurement (Table 6.08). This was likely due to a lack of rainfall during this period leading to poor cover crop and maize growth and canopy closure. For MSUAF 2017, NDVI was higher for the V3 interseeding timing compared with the V6 interseeding timing. When this interaction was sliced, V3 NDVI was significantly higher than NDVI in the V6 plots on June 21 (Table 6.09); no significant difference in NDVI occurred when measurements were taken after the V6 interseeding (Table 6.08).

In SVREC 2017, there were no significant differences in canopy temperature, NDVI, or NDRE when comparing cover crop species, interseeding timings, and seeding rates (Tables 6.10-6.12). For MSUAF 2018, NDVI and NDRE of plots containing oilseed radish and crimson clover were higher compared with the cover crop mixture and annual ryegrass plots (Tables 6.11, 6.12). When measured on 5 July the NDVI of weedy plots was 0.932 compared with an average of 0.918 for all other plots; on 20 July, the NDVI of weedy plots was 0.930 compared with 0.915 for all other plots (Table 6.13). Additionally, for NDRE, the interseeding timing by measurement date interaction was significant: NDRE was greater in the V3 compared with the V6 plots when measured on July 6 (Table 6.14). At the SVREC 2018 site, NDRE for annual ryegrass and mixture plots was greater compared with crimson clover and oilseed radish plots (Table 6.12). Also, NDRE was lower for the weed-free control plots (0.605) compared with all other plots (0.618) when measured on 06 July (Table 6.20). Finally, fall cover crop biomass was poorly correlated with canopy temperature, NDVI, and NDRE in all site years and at all measurement timings (Tables 6.22-6.27).

The observed increases in NDVI and NDRE as the season progressed were likely driven by maize growth and increased canopy closure. The exception to this was at MSUAF 2018, where dry conditions resulted in poor crop growth from early to mid-July. Overall, it appears that cover crops contribute only slightly to increased NDVI and NDRE as increased cover crop biomass did not correlate to higher NDVI and NDRE; secondly, remote sensing did not always detect differences in NDVI and NDRE when cover crops were interseeded. At MSUAF 2017, NDVI was greater in V3 plots compared with V6; however, this measurement was on June 26, prior to the V6 interseeding. Following the V6 interseeding, no differences in NDVI were observed. The increased NDVI and NDRE for MSUAF 2018 in oilseed radish and crimson clover plots was likely driven by differences in weed pressure in those plots or random differences in maize growth. We believe the latter is true, as further analysis of weed emergence and biomass did not show the same correlation (Table 6.28). These differences likely carried over to the other measurement dates as well. The difference in NDRE compared with the weed-free plots on 6 July at the SVREC 2018 location likely indicates that there was a greater amount of plant tissue where cover crops were interseeded compared with the bare soil in the weed-free plots. Finally, the interaction between interseeding timing and measurement time for MSUAF 2018 on July 6 was likely due to the difference in interseeding dates: V6 cover crops had minimal time to emerge prior to this measurement.

Maize Grain Yield

At the SVREC 2017 site, a windstorm prior to harvest caused severe lodging; data from this site year is not reported. At the MSUAF 2017 site, grain yield of the weedy plots averaged 7.4 Mg ha^{-1}, while yields of all other plots ranged from 9.6 to 11.2 Mg ha^{-1} (Brooker et al. 2019). Similarly, for MSUAF 2018, yield of the weedy plots averaged 8.1 Mg ha^{-1}, while yields of all other plots ranged from 10.7 to 13.3 Mg ha^{-1} (unpublished data). For each of these sites, there was no difference in yield comparing weed-free plots to all other plots. At SVREC, weed biomass was negligible in all plots, and no differences in yield were observed comparing treatments (unpublished data). Across all sites, maize yield in cover crop treatments did not differ from yield in the weed-free control (unpublished data).

There was not a strong correlation between canopy temperature and grain yield. For MSUAF 2017, there was a weak negative correlation between canopy temperature and grain yield when measurements were taken on May 29 (R^2 = 0.16) and June 16 (R^2 = 0.13) (Table 6.29). Results comparing NDVI and NDRE were variable between site years. For MSUAF 2017 only, NDVI had a slight negative correlation with yield for each measurement timing: June 21 (R^2 = 0.18), June 30 (R^2 = 0.24), and July 19 (R^2 = 0.17) (Table 6.30). NDRE was also negatively correlated with grain yield at MSUAF 2017 at each measurement timing with R^2 values of 0.21, 0.24, and 0.17, respectively; however, at MSUAF 2018, NDRE was positively correlated with grain yield when measured on July 20 (R^2 = 0.35) (Table 6.30). Since there were no significant differences in corn grain yield, it is not surprising that remotely sensed canopy temperature, NDVI, and NDRE were not moderately correlated with differences in corn grain yield.

Conclusions

Remote sensing detected cover crops in maize prior to canopy closure as evidenced by differences in NDVI and NDRE in some interseeded treatments compared with the weed free control. Farmers interseeding their fields could use remote sensing to view cover crop establishment across varying soil types or topography. Cover crops in our research did not contribute to differences in canopy temperature, an important indicator of crop stress. We were interested in determining if cover crops influenced canopy temperature during maize pollination or grain-fill. Water stress during these times can result in reduced maize grain yield (Otegui et al.

1995; Cakir 2004). Additionally, cover crops could compete with maize for nutrients during pollination and grain fill, two times during the growing season where nitrogen demand increases (Ciampitti and Vyn, 2013). There were no differences in maize yield in the no cover control compared with yield where various cover crop species were seeded at the V3 or V6 growth stages at varying seeding rates. We conclude that cover crops in this system were not competitive with maize and differences in remotely sensed variables including temperature and spectral reflectance were primarily driven by the maize canopy, especially after canopy closure. Additional research with intercropping or seeding cover crops at higher densities is needed to determine the ability of remote sensing to detect changes in maize nutritional status, and water availability when other cash crops or cover crops are growing with maize. Our research contributes to systems modeling efforts to predict crop yields when cover crops are interseeded in various climatic and topographical conditions.

APPENDIX

APPENDIX F

CHAPTER 6 TABLES AND FIGURES

Table 6.01. Corn planting and harvest dates and cover crop seeding dates for each site year.

		Interseeding Timing		
Site Year	Corn Planting	V3	V6	Corn Harvest
Year One				
MSUAF 2017	May 15	June 6	June 23	Oct. 13
MSUAF 2018	May 8	June 3	June 15	Oct. 26
SVREC 2017	Apr. 26	May 26	June 12	Oct. 12
SVREC 2018	May 9	June 5	June 18	Oct. 16

Table 6.02. AirScout flyover dates for each site year.

MSUAF 2017	MSUAF 2018	SVREC 2017	SVREC 2018
29 May	-	30 May	7 May
16 June	-	15 June	23 May
27 June	-	16 June	6 June
6 July	-	28 June	17 June
18 July	-	17 July	1 July
31 July	-	1 August	8 July
20 August	-	4 September	18 July
5 September	-	21 September	3 August
21 September	-	-	22 August
-	-	-	12 September
-	-	-	3 October
-	-	-	16 October

Table 6.03. UAV flyovers dates for each site year.

MSUAF 2017	MSUAF 2018	SVREC 2017	SVREC 2018
21 June	22 May	15 June	15 June
30 June	5 July	22 June	6 July
19 July	20 July	28 June	29 July

Table 6.04. Remotely sensed canopy temperature for East Lansing (MSUAF) and Saginaw Valley (SVREC) in 2017 and 2018 comparing flyover times.

	Site Year			
	MSUAF 2017	SVREC 2017	MSUAF 2018[a]	SVREC 2018
Measurement	Temperature °C			
1	19.0 g[b]	15.5 h	-	17.6 j
2	24.3 b	30.4 a	-	28.9 b
3	20.4 f	21.3 d	-	34.1 a
4	30.4 a	22.5 c	-	29.0 c
5	18.9 h	19.3 e	-	27.4 e
6	21.2 e	18.7 f	-	29.6 b
7	22.7 d	17.9 g	-	23.4 g
8	12.9 i	27.9 b	-	23.5 f
9	23.1 c	-	-	15.9 k
	-	-	-	21.5 h
	-	-	-	19.5 i
	-	-	-	15.5 l
±SEM[c]	±0.04	±0.02	-	±0.03

[a]Temperature data not collected at MSUAF 2018 site.

[b] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[c]Standard error of mean for LSD comparisons.

Table 6.05. MSUAF 2017 remotely sensed canopy temperature comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

			Measurement Date								
Cover Crop	Timing	Rate	5/29	6/16	6/27	7/06	7/18	7/31	8/20	9/05	9/21
							°C				
AR	V3	0.5X	19.1	24.4	20.3	30.3	19.0	21.2	22.6	12.9	23.2
		1X	19.0	24.2	20.5	30.3	18.8	21.2	22.7	12.9	23.4
		2X	19.0	24.2	20.4	30.0	18.9	21.1	22.6	12.9	23.0
	V6	0.5X	19.0	24.3	20.3	30.3	18.9	21.1	22.7	13.0	22.9
		1X	19.1	24.3	20.4	30.5	18.9	21.2	22.7	13.0	22.9
		2X	19.1	24.3	20.3	30.4	18.9	21.3	22.9	13.0	23.0
CC	V3	0.5X	19.0	24.3	20.3	30.3	18.8	21.1	22.6	12.9	23.3
		1X	19.0	24.3	20.4	30.3	18.8	21.1	22.6	12.9	23.2
		2X	19.0	24.3	20.4	30.4	18.8	21.2	22.8	12.8	23.3
	V6	0.5X	19.0	24.3	20.4	30.6	18.9	21.1	22.8	12.9	23.1
		1X	19.0	24.3	20.4	30.4	18.8	21.2	22.6	12.9	23.1
		2X	19.0	24.4	20.4	30.4	18.8	21.2	22.8	13.0	23.0
OR	V3	0.5X	18.9	24.4	20.4	30.6	18.9	21.2	22.7	12.8	23.1
		1X	19.0	24.3	20.4	30.4	18.9	21.2	22.8	12.9	23.2
		2X	19.0	24.3	20.3	30.2	18.9	21.1	22.5	12.9	23.1
	V6	0.5X	19.0	24.3	20.4	30.5	18.9	21.1	22.6	12.9	22.9
		1X	19.0	24.4	20.4	30.4	18.9	21.1	22.6	12.9	22.7
		2X	19.0	24.4	20.5	30.9	19.0	21.2	22.6	13.0	22.9
MIX	V3	0.5X	19.0	24.5	20.3	30.5	18.9	21.2	22.7	12.9	23.2
		1X	19.0	24.3	20.5	30.5	18.8	21.2	22.7	13.0	23.1
		2X	18.9	24.3	20.3	30.3	18.8	21.2	22.5	12.9	23.2
	V6	0.5X	19.0	24.4	20.3	30.4	18.9	21.1	22.6	12.9	23.0
		1X	19.0	24.4	20.4	30.3	18.8	21.1	22.6	13.0	23.0
		2X	19.0	24.3	20.4	30.9	18.9	21.3	22.7	13.0	22.9
Weed-Free			18.9	24.3	20.4	30.4	18.9	21.2	22.6	12.9	22.9
Weedy			19.0	24.3	20.3	30.3	18.8	21.2	22.9	12.9	23.0
±SEM[a]			±0.22	±0.15	±0.12	±0.35	±0.06	±0.17	±0.20	±0.10	±0.18

[a] Standard error of mean for LSD comparisons.

Table 6.06. SVREC 2017 remotely sensed canopy temperature comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	5/30	6/16	6/27	7/06	7/18	7/31	8/20	9/05
			Measurement Date							
			°C							
AR	V3	0.5X	15.5	30.5	21.3	22.6	19.4	18.8	17.9	28.0
		1X	15.5	30.6	21.3	22.6	19.4	18.7	17.9	27.7
		2X	15.5	30.3	21.3	22.5	19.3	18.7	17.9	27.9
	V6	0.5X	15.6	30.3	21.3	22.5	19.3	18.6	17.9	27.9
		1X	15.6	30.5	21.3	22.5	19.4	18.7	17.9	27.8
		2X	15.6	30.4	21.3	22.5	19.3	18.5	17.9	27.9
CC	V3	0.5X	15.4	30.4	21.3	22.6	19.5	18.8	17.9	28.0
		1X	15.5	30.7	21.3	22.6	19.4	18.7	17.9	27.8
		2X	15.4	30.4	21.3	22.5	19.4	18.7	17.9	28.0
	V6	0.5X	15.5	30.5	21.2	22.6	19.3	18.6	17.9	27.7
		1X	15.7	30.6	21.3	22.5	19.4	18.7	17.9	27.9
		2X	15.6	30.5	21.3	22.5	19.3	18.6	17.9	27.7
OR	V3	0.5X	15.5	30.4	21.3	22.5	19.2	18.7	17.9	28.1
		1X	15.5	30.4	21.3	22.5	19.3	18.7	17.9	27.7
		2X	15.4	30.3	21.3	22.5	19.3	18.7	17.9	28.1
	V6	0.5X	15.4	30.4	21.3	22.5	19.2	18.7	17.9	28.0
		1X	15.6	30.5	21.3	22.5	19.2	18.6	17.9	27.8
		2X	15.5	30.4	21.3	22.5	19.3	18.6	17.9	27.7
MIX	V3	0.5X	15.3	30.3	21.3	22.5	19.4	18.8	17.9	28.1
		1X	15.3	30.3	21.3	22.5	19.3	18.7	17.9	27.6
		2X	15.3	30.3	21.3	22.5	19.3	18.7	17.9	28.1
	V6	0.5X	15.4	30.3	21.3	22.5	19.3	18.7	17.9	27.9
		1X	15.4	30.4	21.3	22.6	19.5	18.7	17.9	27.9
		2X	15.5	30.3	21.3	22.5	19.3	18.6	17.9	27.8
Weed-Free			15.5	30.5	21.3	22.5	19.3	18.6	17.9	27.7
Weedy			15.5	30.5	21.3	22.5	19.4	18.7	17.9	27.9
±SEM[a]			0.02	0.01	0.03	0.07	0.06	0.09	0.03	0.16

[a] Standard error of mean for LSD comparisons.

Table 6.07. SVREC 2018 remotely sensed canopy temperature comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	5/07	5/23	6/06	6/17	7/01	7/08	7/18	8/03	8/22	9/12	10/03	10/16
			Measurement Date											
			°C											
AR	V3	0.5X	17.5	28.8	33.835	29.0	27.4	29.8	23.4	23.6	16.0	21.6	19.5	15.6
		1X	17.6	28.8	33.695	29.0	27.3	29.5	23.3	23.6	15.9	21.5	19.5	15.5
		2X	17.5	28.9	33.9725	29.1	27.5	29.6	23.2	23.6	16.0	21.5	19.5	15.6
	V6	0.5X	17.5	28.9	33.87	29.1	27.5	29.6	23.4	23.5	15.9	21.4	19.5	15.5
		1X	17.5	29.0	34.04	29.0	27.5	29.6	23.4	23.6	15.9	21.5	19.5	15.5
		2X	17.5	28.9	33.81	29.1	27.4	29.6	23.4	23.5	16.0	21.4	19.5	15.6
CC	V3	0.5X	17.4	28.8	34.15	29.0	27.4	29.8	23.5	23.6	15.9	21.5	19.4	15.5
		1X	17.6	28.7	34.14	29.0	27.4	29.5	23.5	23.6	15.8	21.5	19.5	15.5
		2X	17.5	28.7	34	29.1	27.5	29.5	23.6	23.6	15.9	21.5	19.5	15.5
	V6	0.5X	17.5	28.7	33.92	29.1	27.5	29.5	23.5	23.5	15.9	21.5	19.5	15.5
		1X	17.6	28.9	34.2425	29.1	27.5	29.7	23.6	23.6	15.9	21.6	19.5	15.5
		2X	17.6	28.7	34.06	29.0	27.5	29.6	23.6	23.6	15.9	21.5	19.5	15.5
OR	V3	0.5X	17.5	28.8	34.225	29.0	27.3	29.7	23.4	23.5	15.9	21.5	19.4	15.6
		1X	17.6	28.8	34.205	29.0	27.3	29.7	23.5	23.6	15.9	21.5	19.5	15.6
		2X	17.5	28.8	34.3025	29.0	27.4	29.7	23.5	23.5	15.9	21.4	19.4	15.6
	V6	0.5X	17.4	28.8	34.28	29.1	27.4	29.7	23.6	23.5	15.9	21.5	19.4	15.5
		1X	17.6	28.8	34.43	29.0	27.4	29.9	23.6	23.6	15.8	21.5	19.4	15.6
		2X	17.5	28.9	34.3875	29.0	27.3	29.6	23.6	23.5	15.9	21.4	19.4	15.6
MIX	V3	0.5X	17.7	28.8	33.9475	29.0	27.1	29.5	23.2	23.5	16.0	21.5	19.5	15.7
		1X	17.7	29.0	33.855	29.0	27.0	29.2	23.2	23.5	16.0	21.4	19.5	15.6
		2X	17.7	29.0	34.0975	29.0	27.2	29.4	23.3	23.5	16.0	21.5	19.5	15.5
	V6	0.5X	17.7	29.0	34.0425	29.1	27.3	29.6	23.4	23.5	16.0	21.5	19.5	15.5
		1X	17.8	29.0	34.19	29.1	27.5	29.5	23.3	23.5	15.9	21.5	19.5	15.5
		2X	17.7	29.0	33.96	29.1	27.5	29.5	23.4	23.5	16.0	21.5	19.5	15.5
	Weed-Free		17.6	28.8	34.1	29.1	27.5	30.0	23.8[a]	23.7[a]	15.9	21.5	19.5	15.5
	Weedy		17.6	28.9	34.1	29.1	27.4	29.5	23.4	23.5	15.9	21.5	19.5	15.5
	±SEM[b]		±0.11	±0.17	±0.16	±0.07	±0.24	±0.22	±0.16	±0.07	±0.05	±0.13	±0.03	±0.05

Table 6.07 (cont'd)

[a] Within columns, means are significantly different compared with the average of all interactions at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.08. Normalized difference vegetation index (NDVI) and normalized difference red-edge (NDRE) for MSUAF and SVREC in 2017 and 2018 comparing UAV flyover times.

	Site Year			
	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
Measurement	NDVI			
1	0.158 c[a]	0.322 c	0.253 b	0.345 c
2	0.621 b	0.716 b	0.918 a	0.874 b
3	0.842 a	0.801 a	0.915 a	0.914 a
±SEM[b]	±0.006	±0.007	±0.001	±0.002
Measurement	NDRE			
1	0.094 c	0.169 c	0.155 c	0.184 c
2	0.379 b	0.424 b	0.680 b	0.618 b
3	0.608 a	0.496 a	0.699 a	0.647 a
±SEM	±0.004	±0.006	±0.002	±0.001

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[b] Standard error of mean for LSD comparisons.

Table 6.09. Interaction between flyover date and cover crop interseeding timing comparing normalized difference vegetation index (NDVI) for MSUAF 2017.

Date	Interseeding Timing	Site Year MSUAF 2017
		NDVI
21 June	V3	0.1725 c[a]
	V6	0.1437 d
30 June	V3	0.6288 b
	V6	0.6137 b
19 July	V3	0.8431 a
	V6	0.8412 a
±SEM[b]		±0.008

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[b] Standard error of mean for LSD comparisons.

Table 6.10. Canopy temperature comparing cover crop species, interseeding timings, and seeding rates for each site year.

	Site Year			
Species	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
	°C			
Annual ryegrass	21.4 a[a]	21.7 a	-	23.8 a
Crimson clover	21.4 a	21.7 a	-	23.8 a
Oilseed radish	21.4 a	21.7 a	-	23.8 a
Mixture	21.4 a	21.7 a	-	23.8 a
±SEM	±0.03	±0.02	-	±0.02
Interseeding Timing				
V3	21.4 a	21.7 a	-	23.8 a
V6	21.4 a	21.7 a	-	23.8 a
±SEM	±0.02	±0.01	-	±0.01
Seeding Rate				
0.5X	21.4 a	21.7 a	-	23.8 a
1X	21.4 a	21.7 a	-	23.8 a
2X	21.4 a	21.7 a	-	23.8 a
±SEM[b]	±0.04	±0.01	-	±0.01

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[b] Standard error of mean for LSD comparisons.

Table 6.11. Normalized difference vegetation index (NDVI) comparing cover crop species, interseeding timings, and seeding rates for each site year.

	Site Year			
Species	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
		NDVI		
Annual ryegrass	0.548 a[a]	0.605 a	0.687 c	0.713 a
Crimson clover	0.536 a	0.605 a	0.700 a	0.709 a
Oilseed radish	0.538 a	0.619 a	0.703 a	0.708 a
Mixture	0.541 a	0.623 a	0.693 b	0.715 a
±SEM	±0.007	±0.008	±0.002	±0.002
Interseeding Timing				
V3	0.541 a	0.608 a	0.695 a	0.712 a
V6	0.533 b	0.618 a	0.696 a	0.710 a
±SEM	±0.005	±0.006	±0.001	±0.001
Seeding Rate				
0.5X	0.542 a	0.615 a	0.695 a	0.712 a
1X	0.539 a	0.612 a	0.696 a	0.712 a
2X	0.536 a	0.612 a	0.696 a	0.710 a
±SEM[b]	±0.006	±0.007	±0.001	±0.002

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[b] Standard error of mean for LSD comparisons.

Table 6.12. Normalized difference red-edge (NDRE) comparing cover crop species, interseeding timings, and seeding rates for each site year.

	Site Year			
Species	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
	NDRE			
Annual ryegrass	0.364 a[a]	0.357 a	0.500 c	0.485 a
Crimson clover	0.367 a	0.357 a	0.517 a	0.480 b
Oilseed radish	0.361 a	0.367 a	0.520 a	0.480 b
Mixture	0.359 a	0.372 a	0.509 b	0.488 a
±SEM	±0.004	±0.007	±0.002	±0.002
Interseeding Timing				
V3	0.362 a	0.362 a	0.513 a	0.485 a
V6	0.358 a	0.364 a	0.510 a	0.482 a
±SEM	±0.003	±0.010	±0.002	±0.001
Seeding Rate				
0.5X	0.362 a	0.366 a	0.511 a	0.484 a
1X	0.361 a	0.362 a	0.514 a	0.483 a
2X	0.358 a	0.361 a	0.510 a	0.482 a
±SEM[b]	±0.004	±0.006	±0.002	±0.001

[a] Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

[b] Standard error of mean for LSD comparisons.

Table 6.13. MSUAF 2017 NDVI comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	6/21	6/30	7/19
				NDVI	
AR	V3	0.5X	0.203	0.652	0.847
		1X	0.162	0.620	0.843
		2X	0.179	0.636	0.847
	V6	0.5X	0.153	0.620	0.845
		1X	0.168	0.632	0.846
		2X	0.154	0.617	0.838
CC	V3	0.5X	0.176	0.628	0.838
		1X	0.143	0.608	0.839
		2X	0.176	0.632	0.844
	V6	0.5X	0.134	0.605	0.842
		1X	0.155	0.621	0.841
		2X	0.144	0.609	0.834
OR	V3	0.5X	0.167	0.638	0.846
		1X	0.148	0.618	0.841
		2X	0.182	0.638	0.847
	V6	0.5X	0.134	0.619	0.847
		1X	0.144	0.627	0.848
		2X	0.116	0.589	0.831
MIX	V3	0.5X	0.198	0.643	0.848
		1X	0.161	0.611	0.837
		2X	0.185	0.636	0.843
	V6	0.5X	0.153	0.627	0.848
		1X	0.152	0.622	0.846
		2X	0.117	0.576	0.829
	Weed-Free		0.137	0.606	0.836
	Weedy		0.167	0.631	0.845
	±SEM[b]		±0.034	±0.033	±0.009

[a] Within columns, means are significantly different compared with the average of all interactions at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.14. SVREC 2017 NDVI comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

			Measurement Date		
Cover Crop	Timing	Rate	6/21	6/30	7/19
				NDVI	
AR	V3	0.5X	0.286	0.699	0.797
		1X	0.277	0.696	0.794
		2X	0.2638	0.726	0.812
	V6	0.5X	0.287	0.732	0.815
		1X	0.325	0.741	0.811
		2X	0.303	0.728	0.806
CC	V3	0.5X	0.308	0.707	0.792
		1X	0.290	0.698	0.787
		2X	0.274	0.714	0.797
	V6	0.5X	0.304	0.725	0.806
		1X	0.339	0.720	0.798
		2X	0.287	0.714	0.791
OR	V3	0.5X	0.382	0.724	0.804
		1X	0.313	0.700	0.798
		2X	0.350	0.714	0.798
	V6	0.5X	0.333	0.715	0.801
		1X	0.366	0.726	0.807
		2X	0.340	0.717	0.790
MIX	V3	0.5X	0.374	0.710	0.800
		1X	0.312	0.705	0.801
		2X	0.335	0.715	0.801
	V6	0.5X	0.329	0.727	0.809
		1X	0.385	0.744	0.801
		2X	0.347	0.721	0.799
	Weed-Free		0.292	0.704	0.793
	Weedy		0.325	0.725	0.806
	±SEM[b]		0.046	0.025	0.019

[a] Within columns, means are significantly different compared with the average of all interactions at $\alpha = 0.05$ according to Fisher's LSD.

[b]Standard error of mean for LSD comparisons.

Table 6.15. MSUAF 2018 NDVI comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	6/21	6/30	7/19
				Measurement Date	
				NDVI	
AR	V3	0.5X	0.236	0.913	0.896
		1X	0.241	0.922	0.918
		2X	0.240	0.909	0.894
	V6	0.5X	0.246	0.914	0.906
		1X	0.242	0.909	0.902
		2X	0.246	0.917	0.912
CC	V3	0.5X	0.253	0.925	0.921
		1X	0.247	0.923	0.921
		2X	0.258	0.923	0.920
	V6	0.5X	0.259	0.921	0.920
		1X	0.262	0.923	0.919
		2X	0.259	0.919	0.919
OR	V3	0.5X	0.268	0.920	0.920
		1X	0.263	0.922	0.922
		2X	0.272	0.923	0.923
	V6	0.5X	0.269	0.918	0.919
		1X	0.271	0.918	0.920
		2X	0.269	0.915	0.919
MIX	V3	0.5X	0.246	0.919	0.914
		1X	0.239	0.917	0.919
		2X	0.247	0.917	0.915
	V6	0.5X	0.248	0.916	0.916
		1X	0.250	0.915	0.913
		2X	0.250	0.915	0.917
	Weed-Free		0.251	0.913	0.917
	Weedy		0.251	0.932[a]	0.930[a]
	±SEM[b]		±0.006	±0.005	±0.008

[a] Within columns, means are significantly different compared with the average of all interactions at α = 0.05 according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.16. SVREC 2018 NDVI comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	6/21	6/30	7/19
				Measurement Date	
				NDVI	
AR	V3	0.5X	0.366	0.882	0.916
		1X	0.356	0.880	0.914
		2X	0.333	0.873	0.915
	V6	0.5X	0.333	0.872	0.916
		1X	0.339	0.866	0.916
		2X	0.358	0.878	0.916
CC	V3	0.5X	0.354	0.872	0.913
		1X	0.349	0.874	0.911
		2X	0.336	0.873	0.913
	V6	0.5X	0.352	0.871	0.913
		1X	0.331	0.867	0.913
		2X	0.337	0.873	0.913
OR	V3	0.5X	0.343	0.871	0.915
		1X	0.360	0.880	0.912
		2X	0.313	0.869	0.911
	V6	0.5X	0.338	0.867	0.910
		1X	0.341	0.866	0.912
		2X	0.346	0.875	0.912
MIX	V3	0.5X	0.351	0.881	0.918
		1X	0.352	0.881	0.918
		2X	0.344	0.878	0.916
	V6	0.5X	0.342	0.874	0.916
		1X	0.350	0.874	0.916
		2X	0.364	0.882	0.917
	Weed-Free		0.338	0.866	0.914
	Weedy		0.354	0.877	0.915
	±SEM[b]		±0.012	±0.006	±0.002

[a] Within columns, means are significantly different compared with the average of all interactions at α = 0.05 according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.17. MSUAF 2017 normalized difference red-edge (NDRE) comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

			Measurement Date		
Cover Crop	Timing	Rate	6/21	6/30	7/19
				NDRE	
AR	V3	0.5X	0.109	0.393	0.609
		1X	0.093	0.372	0.607
		2X	0.105	0.386	0.616
	V6	0.5X	0.091	0.376	0.612
		1X	0.105	0.388	0.615
		2X	0.096	0.375	0.605
CC	V3	0.5X	0.098	0.378	0.600
		1X	0.085	0.368	0.604
		2X	0.098	0.385	0.613
	V6	0.5X	0.081	0.367	0.606
		1X	0.098	0.381	0.608
		2X	0.091	0.374	0.604
OR	V3	0.5X	0.096	0.389	0.609
		1X	0.086	0.379	0.608
		2X	0.100	0.394	0.607
	V6	0.5X	0.082	0.380	0.613
		1X	0.093	0.390	0.616
		2X	0.077	0.365	0.597
MIX	V3	0.5X	0.017	0.390	0.608
		1X	0.093	0.371	0.599
		2X	0.105	0.389	0.611
	V6	0.5X	0.091	0.381	0.611
		1X	0.097	0.384	0.613
		2X	0.077	0.352	0.592
	Weed-Free		0.088	0.371	0.604
	Weedy		0.097	0.388	0.612
	±SEM[b]		±0.014	±0.024	±0.012

[a] Within columns, means are significantly different compared with the average of all interactions at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.18. SVREC 2017 normalized difference red-edge (NDRE) comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	Measurement Date 6/21	6/30	7/19
				NDVI	
AR	V3	0.5X	0.142	0.419	0.499
		1X	0.137	0.410	0.493
		2X	0.115	0.437	0.507
	V6	0.5X	0.128	0.435	0.505
		1X	0.172	0.445	0.507
		2X	0.151	0.434	0.500
CC	V3	0.5X	0.168	0.419	0.493
		1X	0.148	0.406	0.486
		2X	0.129	0.425	0.491
	V6	0.5X	0.150	0.427	0.497
		1X	0.189	0.425	0.490
		2X	0.141	0.420	0.482
OR	V3	0.5X	0.229	0.430	0.504
		1X	0.157	0.406	0.495
		2X	0.195	0.420	0.494
	V6	0.5X	0.173	0.419	0.492
		1X	0.202	0.428	0.499
		2X	0.178	0.419	0.480
MIX	V3	0.5X	0.222	0.424	0.505
		1X	0.157	0.416	0.500
		2X	0.181	0.429	0.499
	V6	0.5X	0.164	0.432	0.501
		1X	0.223	0.444	0.497
		2X	0.187	0.427	0.491
	Weed-Free		0.144	0.412	0.488
	Weedy		0.174	0.427	0.502
	±SEM[b]		0.042	0.020	0.018

[a] Within columns, means are significantly different compared with the average of all interactions at α = 0.05 according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.19. MSUAF 2018 normalized difference red-edge (NDRE) comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

Cover Crop	Timing	Rate	Measurement Date 6/21	6/30	7/19
				NDRE	
AR	V3	0.5X	0.141	0.692	0.662
		1X	0.145	0.712	0.683
		2X	0.144	0.686	0.651
	V6	0.5X	0.148	0.691	0.661
		1X	0.146	0.685	0.654
		2X	0.150	0.692	0.663
CC	V3	0.5X	0.153	0.710	0.698
		1X	0.151	0.711	0.692
		2X	0.159	0.706	0.690
	V6	0.5X	0.159	0.703	0.682
		1X	0.162	0.705	0.689
		2X	0.162	0.697	0.682
OR	V3	0.5X	0.169	0.706	0.691
		1X	0.165	0.708	0.694
		2X	0.170	0.709	0.694
	V6	0.5X	0.169	0.699	0.684
		1X	0.171	0.701	0.691
		2X	0.171	0.692	0.680
MIX	V3	0.5X	0.147	0.703	0.685
		1X	0.146	0.707	0.686
		2X	0.147	0.695	0.679
	V6	0.5X	0.150	0.695	0.677
		1X	0.150	0.691	0.680
		2X	0.153	0.691	0.676
	Weed-Free		0.155	0.689	0.674
	Weedy		0.155	0.705	0.672
	±SEM[b]		±0.007	±0.008	±0.012

[a] Within columns, means are significantly different compared with the average of all interactions at α = 0.05 according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 6.20. SVREC 2018 normalized difference red-edge (NDRE) comparing each cover crop species (AR=annual ryegrass; CC=crimson clover; OR=oilseed radish), interseeding timing, and interseeding rate combination for each measurement date.

			Measurement Date		
Cover Crop	Timing	Rate	6/21	6/30	7/19
				NDVI	
AR	V3	0.5X	0.197	0.629	0.651
		1X	0.193	0.628	0.649
		2X	0.176	0.617	0.648
	V6	0.5X	0.178	0.613	0.647
		1X	0.181	0.611	0.649
		2X	0.192	0.624	0.650
CC	V3	0.5X	0.190	0.618	0.647
		1X	0.187	0.619	0.641
		2X	0.176	0.616	0.642
	V6	0.5X	0.188	0.614	0.642
		1X	0.176	0.607	0.640
		2X	0.180	0.616	0.643
OR	V3	0.5X	0.182	0.616	0.649
		1X	0.195	0.624	0.644
		2X	0.165	0.609	0.639
	V6	0.5X	0.179	0.610	0.643
		1X	0.181	0.606	0.640
		2X	0.185	0.619	0.644
MIX	V3	0.5X	0.187	0.629	0.655
		1X	0.190	0.627	0.654
		2X	0.183	0.623	0.650
	V6	0.5X	0.182	0.616	0.652
		1X	0.186	0.618	0.651
		2X	0.195	0.628	0.653
	Weed-Free		0.179	0.605*[a]	0.640
	Weedy		0.191	0.620	0.648
	±SEM[b]		±0.008	±0.006	±0.004

[a] Within columns, means are significantly different compared with the average of all interactions at α = 0.05 according to Fisher's LSD.

[b]Standard error of mean for LSD comparisons.

Table 6.21. Interaction between flyover date and cover crop interseeding timing comparing normalized difference red-edge (NDRE) for MSUAF 2017.

Date	Interseeding Timing	Site Year MSUAF 2017
		NDRE
22 May	V3	0.158 d[a]
	V6	0.153 d
5 July	V3	0.704 a
	V6	0.695 b
20 July	V3	0.684 c
	V6	0.677 c
±SEM[b]		±0.003

[a] Means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b] Standard error of mean for LSD comparisons.

Table 6.22. Correlation between canopy temperature and annual ryegrass biomass for each site year at each flyover measurement time.

	Site Year			
Measurement	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
		R^{2a}		
1	0.02	0.00	-	0.01
2	0.03	0.01	-	<0.01
3	0.01	0.02	-	0.01
4	0.00	0.02	-	0.02
5	0.05	0.02	-	0.03
6	0.01	0.08	-	0.04
7	<0.01	0.02	-	<0.01
8	0.05	0.04	-	<0.01
9	0.02	-	-	0.01
10	-	-	-	0.06
11	-	-	-	<0.01
12	-	-	-	0.18

[a] Coefficient of determination.

Table 6.23. Correlation between canopy temperature and crimson clover biomass for each site year at each flyover measurement time.

Measurement	Site Year			
	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
		R^{2a}		
1	0.03	0.02	-	0.15
2	0.02	0.03	-	0.12
3	<0.01	0.01	-	0.13
4	0.04	0.04	-	0.14
5	0.10	0.01	-	0.14
6	0.01	0.01	-	0.09
7	0.02	0.00	-	<0.01
8	0.08	0.02	-	<0.01
9	0.03	-	-	0.02
10	-	-	-	0.03
11	-	-	-	0.01
12	-	-	-	0.01

[a] Coefficient of determination.

Table 6.24. Correlation between canopy temperature and oilseed radish biomass for each site year at each flyover measurement time.

	Site Year			
Measurement	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
		R^{2a}		
1	0.03	<0.01	-	0.09
2	0.03	0.01	-	0.07
3	0.02	<0.01	-	0.02
4	0.06	0.04	-	0.04
5	0.05	0.02	-	0.10
6	<0.01	0.03	-	0.03
7	<0.01	0.05	-	0.03
8	0.01	0.02	-	0.03
9	0.08	-	-	0.06
10	-	-	-	0.10
11	-	-	-	<0.01
12	-	-	-	0.07

[a] Coefficient of determination.

Table 6.25. Correlation between canopy temperature and the cover crop mixture biomass for each site year at each flyover measurement time.

	Site Year			
Measurement	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
		R^{2a}		
1	0.00	<0.01	-	0.01
2	<0.01	0.07	-	0.01
3	<0.01	0.05	-	0.00
4	0.03	0.07	-	<0.01
5	0.01	0.08	-	0.01
6	0.01	0.03	-	0.02
7	<0.01	0.01	-	0.01
8	0.01	0.02	-	0.04
9	0.01	-	-	0.03
10	-	-	-	0.01
11	-	-	-	<0.01
12	-	-	-	0.04

[a] Coefficient of determination.

Table 6.26. Correlation between normalized difference vegetation index and cover crop biomass for each site year, cover crop species, and UAV flyover time. Data are combined over cover crop seeding rates.

		Site Year			
		MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
Cover Crop	Measurement	R^{2a}			
Annual ryegrass	1	0.05	0.03	0.01	0.00
	2	0.08	<0.01	<0.01	0.01
	3	0.11	0.01	<0.01	<0.01
Oilseed Radish	1	0.07	<0.01	<0.01	0.14
	2	0.05	0.01	<0.01	0.03
	3	0.05	<0.01	0.06	0.05
Crimson Clover	1	0.10	<0.01	0.01	0.01
	2	0.07	<0.01	<0.01	<0.01
	3	0.08	<0.01	<0.01	<0.01
Mixture	1	0.02	0.04	<0.01	0.01
	2	0.01	0.04	0.02	0.00
	3	0.01	0.03	<0.01	0.02

[a] Coefficient of determination.

Table 6.27. Correlation between normalized difference red-edge and cover crop biomass for each site year, cover crop species, and UAV flyover time. Data are combined over cover crop seeding rates.

		Site Year			
		MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
Cover Crop	Measurement	R^{2a}			
Annual ryegrass	1	0.10	0.03	0.01	<0.01
	2	0.18	0.01	0.00	0.02
	3	0.10	0.02	<0.01	0.02
Oilseed Radish	1	0.04	<0.01	<0.01	0.14
	2	0.03	0.02	0.01	0.10
	3	0.03	0.01	0.02	0.13
Crimson Clover	1	0.08	<0.01	0.01	0.01
	2	0.08	<0.01	<0.01	0.08
	3	0.09	0.01	0.03	0.09
Mixture	1	0.01	0.04	<0.01	0.01
	2	0.01	0.05	0.02	<0.01
	3	0.02	0.06	<0.01	0.08

[a] Coefficient of determination.

Table 6.28. Correlation between normalized difference vegetation index (NDVI) and normalized difference red-edge (NDRE) and weed biomass for MSUAF 2018 for each flyover time.

Measurement	NDVI	NDRE
	R^{2a}	R^{2a}
1	0.00	<0.01
2	<0.01	0.01
3	<0.01	0.01

[a] Coefficient of determination.

Table 6.29. Correlation between canopy temperature and the corn grain yield for each site year at each flyover measurement time.

	Site Year			
Measurement	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
		R^{2a}		
1	0.16	-	-	0.06
2	0.13	-	-	0.05
3	0.01	-	-	0.05
4	0.03	-	-	0.06
5	0.08	-	-	0.07
6	0.01	-	-	0.01
7	0.06	-	-	0.01
8	0.05	-	-	<0.01
9	<0.01	-	-	<0.01
10	-	-	-	0.10
11	-	-	-	0.10
12	-	-	-	0.01

[a] Coefficient of determination.

Table 6.30. Correlation between normalized difference vegetation index (NDVI) and normalized difference red-edge (NDRE) and the corn grain yield for each site year at each flyover measurement time.

	Site Year			
Measurement	MSUAF 2017	SVREC 2017	MSUAF 2018	SVREC 2018
NDRE		R^{2a}		
1	0.18	-	0.04	0.06
2	0.24	-	0.01	0.09
3	0.17	-	0.07	0.04
NDVI		R^{2a}		
1	0.21	-	0.08	0.06
2	0.24	-	0.10	0.08
3	0.17	-	0.35	0.05

[a] Coefficient of determination.

Figure 6.01. Daily precipitation and air temperature, and canopy temperature at each flyover date for the MSUAF 2017 (a), SVREC (SV) 2017 (b), and SVREC (SV) 2018 (c) site years.

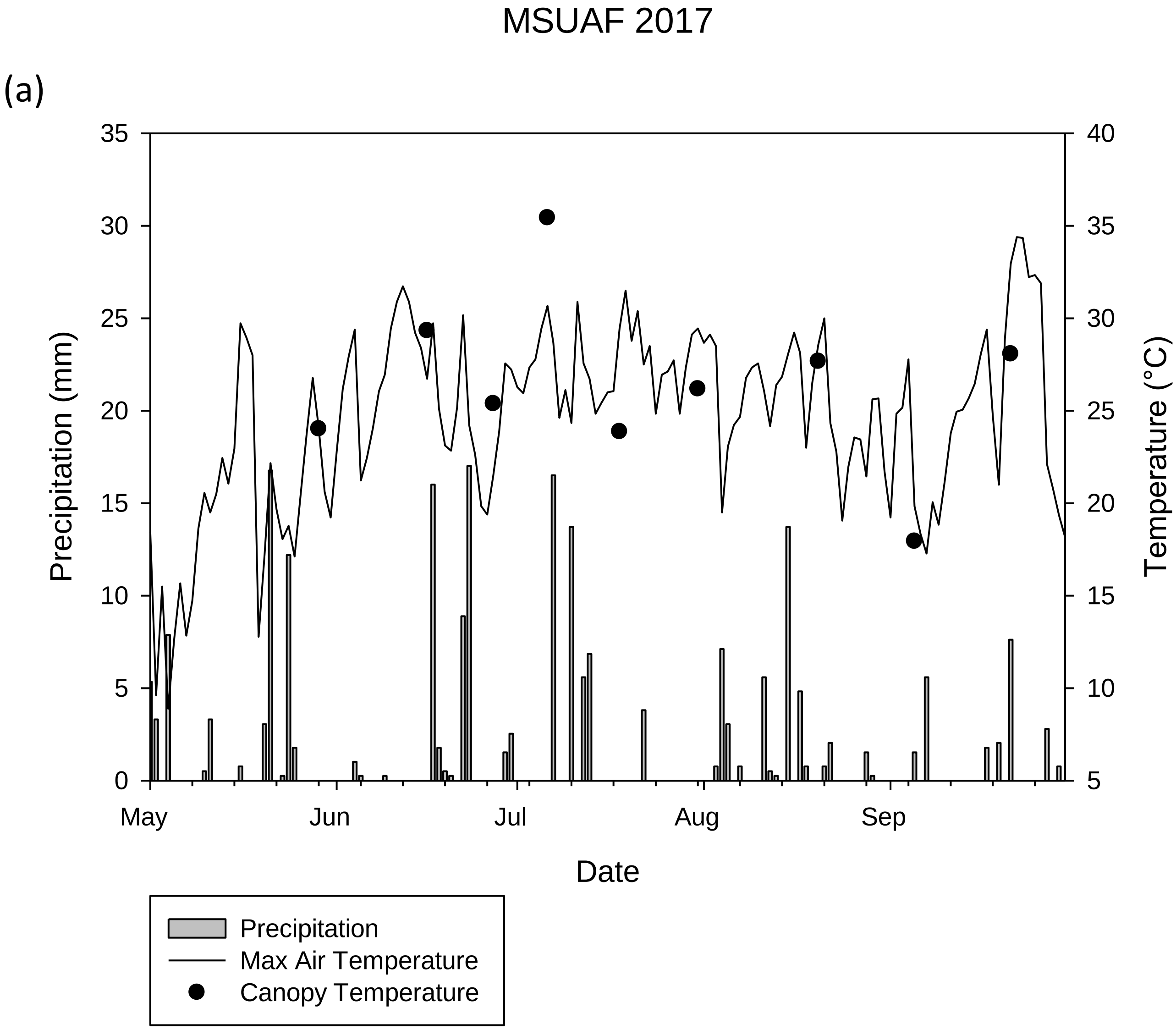


Figure 6.01 (cont'd)

(b)

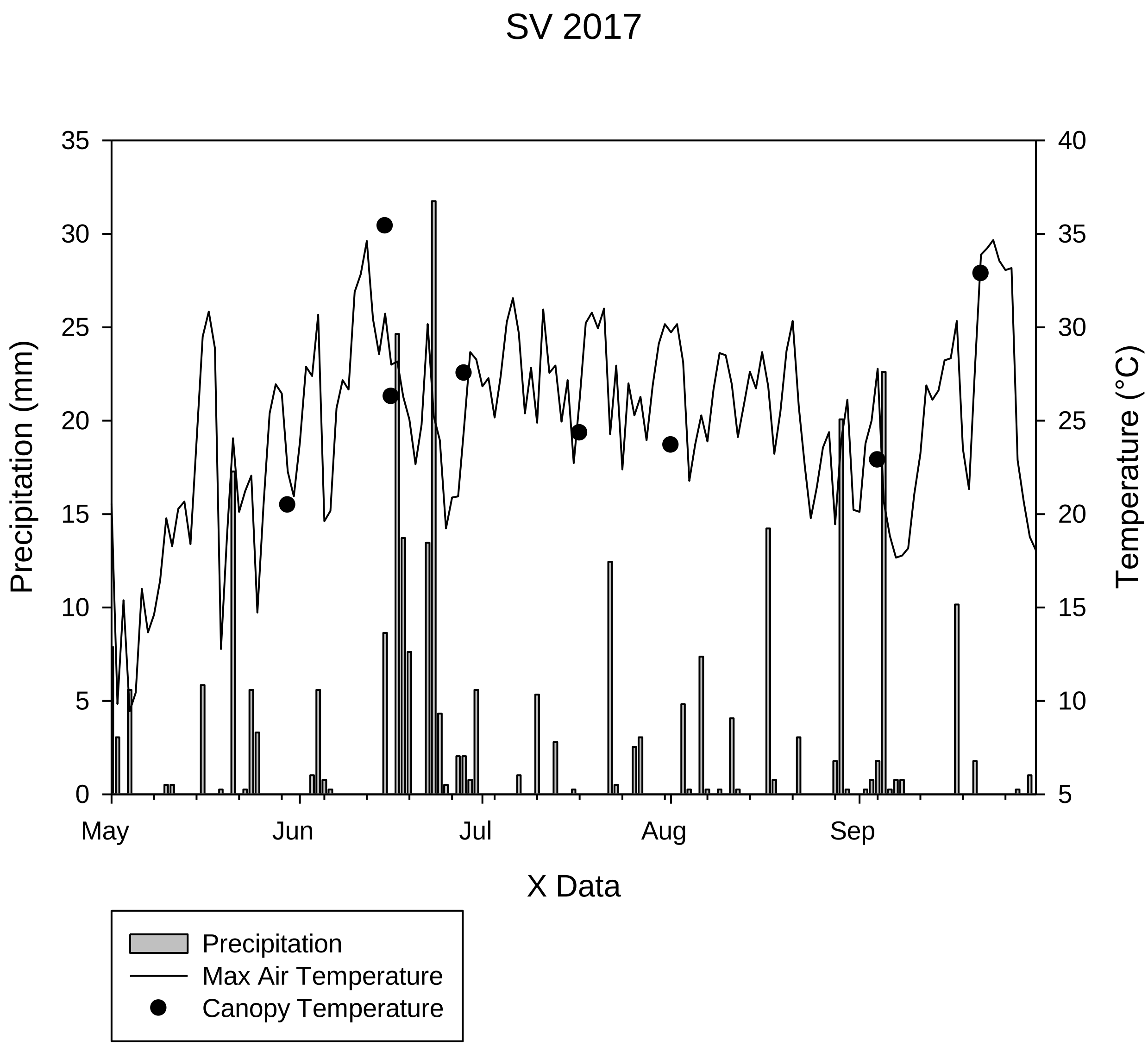
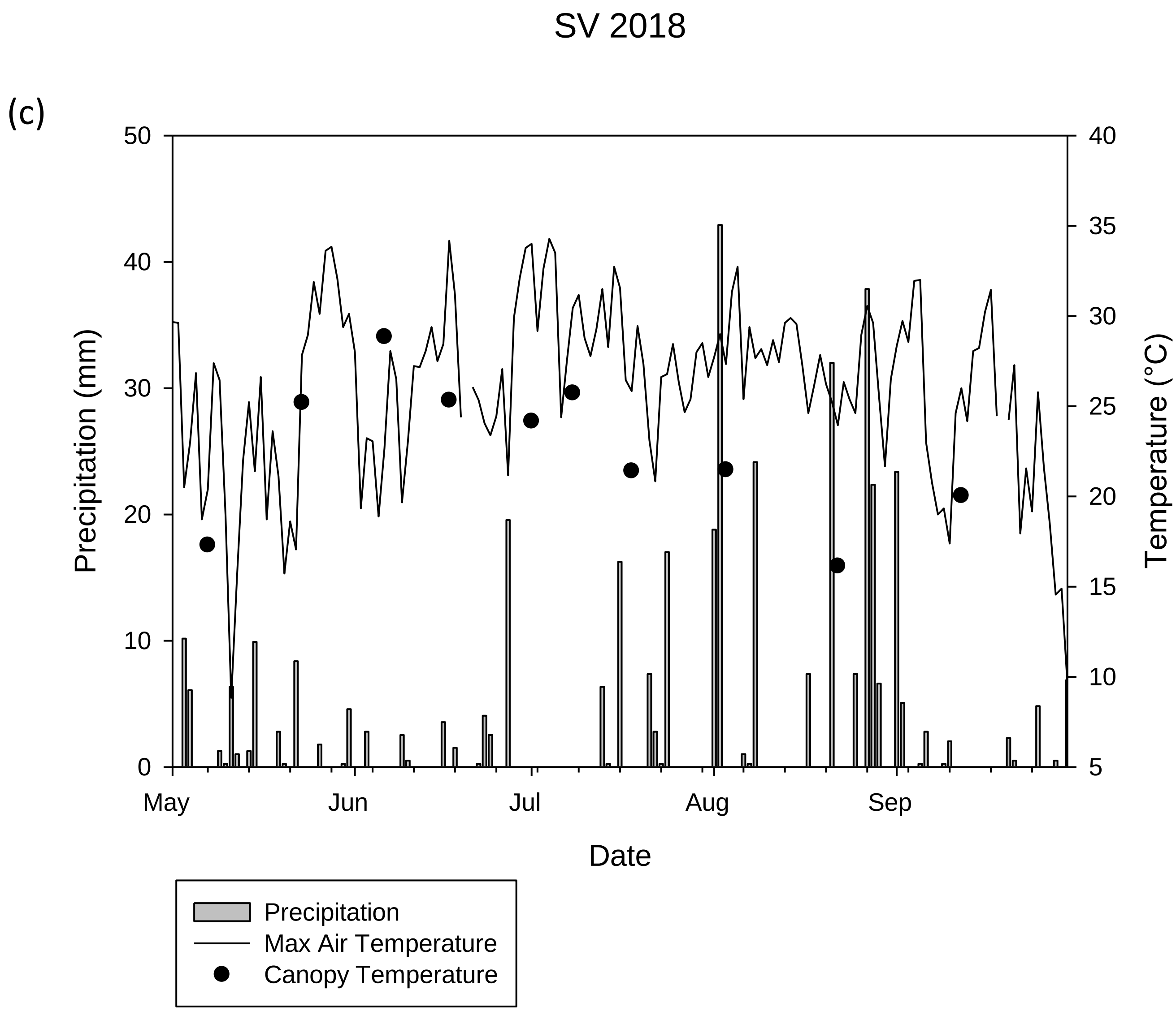


Figure 6.01 (cont'd)



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CHAPTER 7

EVALUATION OF INTERSEEDED COVER CROPS AT MULTIPLE LOCATIONS THROUGHOUT MICHIGAN

Abstract

Broadcast interseeding cover crops in corn from the V2-V7 corn growth stages provides farmers the opportunity to establish cover crops over large areas quickly compared with drilled interseeders. There is limited published information on the establishment and biomass production of broadcast interseeded cover crops and remote sensing has not been utilized to measure corn response to cover crops interseeded in farm fields. The objectives of this research were to evaluate broadcast interseeded cover crop establishment and biomass production as well as cover crop competitiveness with corn across farmer's fields in Michigan. In 2017 and 2018, annual ryegrass, crimson clover, and oilseed radish were broadcast interseeded at the V3 and V6 corn growth stages in nine farm fields. Cover crop density was measured 30 days after interseeding, and cover crop density and biomass were measured in October prior to grain corn harvest. Canopy temperature was measured remotely during the growing season using fixed-wing aircraft to determine the response of corn to interseeded cover crops. Cover crop density varied across site-years; annual ryegrass usually had the highest density; however, fall biomass production of oilseed radish was usually equal to or greater than annual ryegrass and crimson clover biomass. Rainfall during the interseeding period improved cover crop emergence. Cover crop density and the resulting biomass production was higher in sites that were tilled compared with no-till, likely due to better seed to soil contact. Overall, remote sensing during the growing season did not detect a corn response to interseeded cover crops, and grain yield did not differ in the cover crop

versus no cover crop control treatments. Successfully establishing cover crops by broadcast interseeding in corn is dependent on specific location conditions, but conventional tillage and rainfall improve establishment and biomass production.

Introduction

Cropping system diversity increases productivity by enhancing soil biodiversity and nutrient cycling (Tiemann et al. 2015; McDaniel et al. 2014). Cropping systems in the Midwestern United States are usually limited to maize (*Zea mays* L.), soybean (*Glycine max* L. merr), and wheat (*Triticum aestivum* L.) (Aguilar et al. 2015). Adding cover crops is one way to increase plant diversity in a continuous corn, corn-soybean, or corn-soybean-wheat rotation. Cover crops provide a variety of ecosystem services including protecting soil from erosion (Panagos et al. 2015), improving soil quality (Clark 2007), biological N fixation (Dabney et al. 2010), and suppressing pests (O'Reilly et al. 2011); however, establishing cover crops is difficult during the limited number of field days following grain harvest (Baker and Griffis 2009).

Interseeding cover crops early in the corn life cycle may provide farmers with another option for seeding a cover crop (CTIC, 2017). Annual ryegrass (*Lolium multiflorum* Lam.) and crimson clover (*Trifolium incarnatum* L.) (Curran et al. 2018; Belfry and Van Eerd 2016; Grabber et al. 2014; Zhou et al. 2000), as well as oilseed radish (*Raphanus sativus* L.) (Belfry and Van Eerd 2016; Roth et al. 2015) have been successfully interseeded after the V2 corn growth stage (Abendroth et al. 2011) without reducing corn grain yield. The majority of this research was in small plots; only Curran et al. (2018) evaluated drill interseeded cover crop performance in on-farm strip trials.

Using a modified grain drill to interseed cover crops is a slow process and reduces farmer efficiency. Broadcast interseeding provides farmers an option to cover large areas much faster, which may appeal to some farmers and increase adoption of cover crop interseeding. However, a major concern with broadcast interseeding is poor cover crop establishment. Drilling or broadcasting cover crops followed by some incorporation method improved cover crop establishment compared with broadcast seeding alone due to improved seed-to-soil contact (Noland et al. 2018). Rainfall following cover crop seeding is crucial to attain good establishment (Tribouillois et al., 2018; Constantin, 2015; Wilson et al., 2014; Collins and Fowler, 1992), and cover crop establishment on no-till acreage is an important research area with limited published information.

Although research has shown that cover crops can be interseeded in corn after the V2 growth stage without reducing corn grain yield, the mechanisms by which cover crops could potentially enhance corn growth or alternatively compete with corn on farmer field scale sites in the upper Midwest has not been determined. Topography and soil type vary throughout many farm fields, and interspecific competition of cover crops with corn may occur, or cover crops may enhance nutrient cycling and availability to corn. Remote sensing is a methodology utilized by many crop consultants, farmers and researchers to monitor crops in farm fields (Mulla 2013). Measuring canopy temperature with fixed-wing thermal imagery estimates the transpiration rates of plants, which is an indicator of water stress and photosynthetic rates (Maestrini and Basso, 2018). There is currently no published research evaluating corn response to interseeded cover crops using remote sensing throughout the growing season. The objectives of our research were to use remote sensing to monitor corn response to interseeded cover crops in farmer’s fields throughout Michigan, and ground truth thermal imagery data with cover crop density and biomass, and corn yield data.

Materials and Methods

Field experiments were conducted in 2017 and 2018 at nine locations throughout Michigan representing many of the corn-producing regions of the state (Table 7.01). Fields were selected based on farmer interest and ability to broadcast interseed cover crops; farmers made all field and crop management decisions except for the cover crop species and interseeding timings. Interseeders included both a broadcast spreader that overseeded the cover crops as well as specially designed interseeders with drop tubes to spread seed between the corn rows. Glyphosate (N-(phosphonomethyl)glycine)-resistant corn was planted in 76-cm rows between 28 April and 31 May at populations ranging from 69,160-83,980 seeds ha^{-1} (Table 7.01). Weeds were managed with tillage or a burndown herbicide application prior to planting corn. Annual ryegrass, crimson clover, and oilseed radish (Center Seeds, Sydney, OH) were interseeded in strips parallel with corn rows at the V3 and V6 corn stages. V3 interseeded dates ranged from 1 June-19 June, and V6 dates ranged from 14 June-5 July (Table 7.01). Interseeded strip width ranged from 6 corn rows to 40 corn rows based on the width of the interseeder. Recommended seeding rates were 16.8, 22.4, and 11.2 kg ha^{-1} for annual ryegrass, crimson clover, and oilseed radish, respectively, but rates varied somewhat based on farmer preferences (Table 7.01). Strips were replicated either three or four times depending on spatial constraints and no cover control strips were always included; strip length varied between locations based on each farmer’s field dimensions. At the Springport 2017 and 2018 sites, randomization of treatments was forced so additional subsamples were collected to capture variability across the cover crop strips.

Precipitation data were collected throughout the growing seasons from a network of weather stations located throughout Michigan using the nearest measurement station to each field within the Enviro-weather Network (Enviro-weather, 2019) (Table 7.02). Flyovers by the airborne imaging company, Airscout (Monee, IL) were conducted multiple times throughout the growing season from May-October. Flyovers were conducted at seven of the nine locations and excluded Hillman 2017 and 2018. Canopy surface temperature was measured using a thermal sensor.

Cover crop emergence was evaluated 30 days after each interseeding (DAI) timing within $0.25m^2$ quadrats placed between corn rows. Subsample number ranged from 2-10 based on the width and length of the cover crop strips at each site. In October, prior to corn harvest, cover crop density was measured in the same size quadrats as described above, and aboveground biomass was harvested, dried in an oven at 80°C for a minimum of three days, and weighed. Corn was harvested for grain in each cover crop and the no cover crop control strips; yield was recorded using either a combine yield monitor or a weigh wagon and adjusted to 15.5% moisture.

Statistical Analyses

SAS 9.4 (SAS Institute Inc., Cary, NC, USA, 2012) was used for all data analysis. Cover crop and corn performance varied between sites, so each site was analyzed separately. The MIXED procedure was used to compare the fixed effects of cover crop species, interseeding timing, and the interaction for cover crop emergence 30 DAI and in October, cover crop biomass in October, corn grain yield, and canopy temperature. Replication was considered a random effect. For canopy temperature, the flyover time was analyzed as a repeated measure using a compound symmetry covariance structure. The effect of tillage system on cover crop establishment and biomass production was also analyzed using the MIXED procedure. Comparisons of least square means at $P \leq 0.05$ were made if F tests were significant ($P \leq 0.05$) using t tests conducted by the SAS pdmix800 macro (Saxton, 1998). The REG procedure was used to determine the correlation between cover crop biomass and canopy temperature. The slope was different from zero when the model was significant at $P \leq 0.05$. The proportion of variance in canopy temperature explained by cover crop biomass was determined using the coefficient of determination (R^2).

Results and Discussion

Cover Crop Emergence

Cover crop density 30 days after V3 interseeding was equal to or greater than the density 30 d after the V6 interseeding in all site years except Hillman in 2017 (Table 7.05). Annual ryegrass, crimson clover, and oilseed radish densities ranged from 3-201, 4-105, and 9-52 plants m^{-2}, respectively, when combined over interseeding timings (Table 7.05). Average emergence as a percent of the seeded rate was 8, 7, and 22% for annual ryegrass, crimson clover, and oilseed radish, respectively (Tables 7.03 and 7.04). At three sites, Clayton 2017, Hickory Corners A 2017, and Hickory Corners 2018, annual ryegrass density was equal to that of crimson clover and oilseed radish. At four of the sites, Hillman, Springport, Hickory Corners B, and Hart all in 2017, annual ryegrass density exceeded crimson clover and oilseed radish densities (Table 7.05). At the Springport 2018 site only, oilseed radish density was greater than annual ryegrass and crimson clover densities (Table 7.05). Crimson clover density was greater than oilseed radish density at the Hillman 2017 site only (Table 7.05).

By October, cover crop density was similar for the V3 and V6 interseedings in all site years except the Hart 2017 location (Table 7.06.) Annual ryegrass, crimson clover, and oilseed radish densities ranged from 1-173, 1-40, and 14-25 plants m^{-2}, respectively, when combined over interseeding timings (Table 7.06). Annual ryegrass densities were similar or greater compared with the 30 DAI measurements, indicating the potential for more emergence throughout the season. Oilseed radish densities were also similar comparing 30 DAI and October measurements with the exception of the Hillman 2018 site. For both of these species, the carrying capacity of the seeded area was not exceeded. Crimson clover densities declined during the growing season, suggesting that either the carrying capacity for the seeded area was exceeded and intraspecific competition occurred or that crimson clover seedlings did not tolerate conditions under the corn canopy and died. Annual ryegrass density in the fall was greater than crimson clover and oilseed radish densities in four of the eight site years and greater than oilseed radish in only one site year. At Hickory Corners A 2017 and Springport 2018, cover crop species had similar densities despite vastly different seeding rates (Table 7.06). Oilseed radish density was greater than annual ryegrass and crimson clover densities at the Hickory Corners 2018 site (Table 7.06).

Other researchers have shown that rainfall following interseeding is critical for cover crop establishment (Tribouillois et al., 2018; Constantin, 2015; Wilson et al., 2014; Collins and Fowler, 1992), and some of our sites with higher precipitation (Table 7.02) did have greater cover crop densities (KBS B, Hillman 2017) (Tables 7.05 and 7.06); however, this was not always the case. For example, the Clayton 2017 site received 140mm of precipitation during the interseeding period (Table 7.02) but had relatively low cover crop density numbers. Conversely, the Hillman location received the lowest precipitation of any site during the interseeding period

(55mm) but had relatively high cover crop density. Since precipitation did not explain emergence patterns well, we decided to compare fields that were tilled (<30% crop residue) and those that were not tilled or where conservation tillage was used, as this was one of the only major management differences between sites. Results from this analysis showed that at 30 DAI, annual ryegrass and crimson clover densities were higher when seeded into conventionally tilled fields compared with no-till fields, and annual ryegrass density was higher at harvest in conventionally tilled compared to no-till fields (Table 7.07). It is likely that more seeds fell into cracks in the soil and had better seed-to-soil contact for improved emergence in conventionally tilled fields, and less seed-to-soil contact occurred in conservation tillage systems, including no-till. Furthermore, crop residues may have prevented a seed from reaching the soil or may have inhibited light interception by newly emerged seedlings.

Cover Crop Biomass

Cover crop biomass was greater when interseeded at the V3 timing compared with the V6 timing at the Springport 2017, KBS B 2017, and KBS 2018 sites (Table 7.08). Oilseed radish, annual ryegrass, and crimson clover biomass ranged from 63-1103 kg ha^{-1}, 0-612 kg ha^{-1}, and 0-539 kg ha^{-1}, respectively, when combined across interseedings (Table 7.08). Annual ryegrass biomass was comparable to interseeded annual ryegrass biomass in Pennsylvania (250 kg ha^{-1}; Curran et al. 2018) and in dry years in Quebec (400 kg ha^{-1}; Zhou et al. 2000). Oilseed radish biomass was less than that observed in Quebec (1767 kg ha^{-1}); however, Quebec research evaluated sweet corn rather than field corn (Belfry and Van Eerd 2016). Crimson clover biomass was comparable to biomass produced in sweet corn in Quebec (507 kg ha^{-1}; Belfry and Van Eerd 2016). At the Clayton and Hillman sites in 2017, all cover crop species produced similar biomass, while at the Hart 2017 and Hillman 2018 sites, oilseed radish produced more biomass compared with crimson clover only, and more biomass compared with both annual ryegrass and crimson clover in all other site years (Table 7.08). Annual ryegrass produced more biomass compared with crimson clover at the Hillman 2018 site year only, with values of 248 and 46 kg ha^{-1}, respectively.

Cover crop biomass was greater in fields conventionally tilled compared with those under conservation tillage (Figure 7.01). Combined over interseeding timings, annual ryegrass produced 366 kg ha^{-1} in tilled fields compared with only 38 kg ha^{-1} in no-till fields, crimson clover produced 334 kg ha^{-1} compared with 47 kg ha^{-1} in no-till fields, and oilseed radish produced 479 kg ha^{-1} in tilled fields compared with 246 kg ha^{-1} in no-till fields (Table 7.07). The cover crop density and biomass results indicate greater seed-to-soil contact in tilled fields may improve cover crop establishment and biomass production throughout the season. Additionally, total biomass production at the Hillman 2017 (conventional till) and KBS B 2017 (no-till) was very high (Figure 7.01). We believe that increased cover crop light interception occurred at these sites due to lower corn yields (both sites), reduced corn population (KBS B 2017), and possibly earlier crop senescence at the northernmost site (Hillman). Low corn populations have lower leaf area index (LAI) and light interception (Subedi et al. 2006) and lowering corn populations improved the success of interseeding (Baributsa et al. 2008). A shorter maturing corn hybrid was planted at the Hillman site in 2017 and earlier senescence and a lower corn yield occurred at this northern location. Cover crops were harvested in early to mid-October; the first freeze at Hillman occurred on 16 October, while at KBS, it occurred later on 25 October. Many factors influence the establishment of cover crops including precipitation, tillage, corn hybrid, population, and row spacing, growing degree days, and the length of the cover crop growing season.

The correlation between fall cover crop density and biomass was low with R^2 values of 0.23, 0.03, and 0.06 for annual ryegrass, crimson clover, and oilseed radish, respectively (Figures 7.02, 7.03, and 7.04). Cover crop biomass is likely more highly correlated to light penetration into the canopy and continued rainfall during the growing season to sustain both cover crops and corn. We did not determine if higher cover crop seeding rates resulted in greater cover crop biomass in these on-farm strip trials; in small plot research higher seeding rates increased or had no effect on cover crop density and fall cover crop biomass (unpublished data).

Cover Crop Competition with Corn

Remote sensing of canopy temperature was used as one method to detect cover crop competition with corn. Cover crops did not moderate canopy temperature compared with the no cover crop control plots in all site years except KBS A in 2017 (data not shown). Canopy temperature in the V6 plots was higher compared with V3 plots at KBS A in 2017 through mid-July, but there were no differences later in the growing season (Table 7.10). Reduced temperatures in the V3 interseeding were likely caused by actively growing cover crops and possibly weeds that provided soil cover, whereas, V6 plots were seeded later when fewer weeds were emerging. This effect was only evident until mid-July likely due to corn canopy closure after that time. The correlation between canopy temperature and cover crop biomass was poor at all locations and measurement dates (Tables 7.11-7.17). The highest R^2 value was 0.52 at the Springport 2017 site; at this site, there was little temperature variation and only six data points (Table 7.12). All other sites having greater variation in temperature and a higher sample size had lower R^2 values, suggesting that cover crops did not cause additional stress to corn, nor provide a benefit to the corn during the growing season.

Cover crops did not enhance nor reduce corn grain yield in any site year with the exception of Clayton 2017. At this site, corn yielded less where oilseed radish was interseeded at V6 compared with the no cover control (Table 7.9). This location received sufficient rainfall (Table 7.2), and cover crop biomass was quite low compared with other locations (Table 7.8); therefore, we do not believe that cover crops were the actual cause of yield variability at this site. At all other sites, there were no differences in corn grain yield when compared with the untreated no cover crop control (Table 7.9).

The correlation between corn grain yield and remotely sensed canopy temperature was very low at most sites at most measurement dates (Tables 7.11-7.16). The highest correlations were at the Springport 2017 and 2018 sites; however, the sample size was 6 and 8, respectively, and differences in yield (0.2 Mg ha^{-1}, 2017; 0.4 Mg ha^{-1} 2018) and temperature (less than 1°C for all flyover dates) were small (Tables 7.12 and 7.15). Correlations between corn grain yield and canopy temperature were variable, when combined over locations for similar measurement dates. In 2017, positive correlations occurred when measurements were taken on 29-30 May and 15-16 June; R^2 values were 0.62 and 0.67, respectively (Figures 7.05, 7.06). A negative correlation occurred on 19-20 August with an R^2 value of 0.81. In 2018, corn grain yield was negatively correlated with temperature when measured on 3/5 August (R^2=0.77; Figure 7.14); corn grain yield was positively correlated with temperature when measured on 22 August and 16 October with R^2 values of 0.65 and 0.61, respectively (Figures 7.15, 7.17). Research has shown that temperatures of up to 30°C are beneficial to corn growth, and temperatures >30°C for one day or more can cause reductions in corn grain yield (Schlenker and Roberts 2009). The pollination reproductive stage which usually occurs in July in the U.S. is particularly sensitive to high temperatures (Hatfield and Prueger 2015; Hatfield et al. 2011; Schlenker and Roberts 2009), and high night temperatures during grain fill increases respiration and reduces kernel weight (Hatfield et al. 2011). On our measurement dates, we rarely had temperatures greater than 30°C, and results varied between increasing and decreasing corn yields in response to temperature. More frequent measurement dates across multiple sites may be required to determine a corn grain response to temperature. Ultimately, however, a variety of management and environmental factors likely cause differences in corn grain yield across field sites, but interseeded cover crops did not affect grain yield in our research.

Conclusions

Cover crops can be broadcast interseeded in corn in June after the V2 growth stage in various farm production systems without impacting corn grain yield. Many factors affect the establishment of interseeded cover crops in corn; however, our results indicate that some form of tillage prior to or at the time of interseeding can improve cover crop establishment and biomass production, regardless of cover crop species. Other factors that influence the success of interseeded cover crops are precipitation during the interseeding period, which we defined as one week prior to through 30 days after interseeding, and light penetration through the corn canopy in fields following interseeding and again in the early fall as corn senesces, which will be affected by corn hybrid selection, growing degree days, and yield potential. The desired ecosystem benefits of different cover crop species should be considered when choosing a species to interseed. Oilseed radish was the most successful species in this experiment as it produced as much or more biomass compared with annual ryegrass and crimson clover at all locations.

However, oilseed radish winter kills and soil erosion could be a problem the following spring. Annual ryegrass and crimson clover biomass production were more variable, but these species were successfully interseeded in conventionally tilled fields and in fields with greater light penetration and adequate precipitation. Annual ryegrass provides farmers with an overwintering cover crop option. Crimson clover could provide N to a subsequent crop; however, it does not consistently overwinter in Michigan. Cover crop mixtures were not evaluated in this experiment; some of the farmer cooperators are interseeding mixtures to ensure establishment of at least one species within a field area and potentially providing multiple ecosystem services. Further research should evaluate a broader range of cover crop species and mixtures with varying proportions of grass seed to optimize establishment of all cover crop species (Murrell et al. 2017; Finney et al. 2016; Hayden et al. 2014; Wortman et al. 2012). Additional knowledge on how soil surface residues influence interseeding success would be beneficial to provide farmers with better recommendations for interseeding cover crops across a broad range of farming systems. It would be of interest to compare interseeded cover crops at high densities, weeds and intercropped cash crops to determine if remote sensing throughout the growing season can detect a difference in corn canopy temperature in the presence or absence of weeds and beneficial plant species.

APPENDIX

APPENDIX G

CHAPTER 7 TABLES AND FIGURES

Table 7.01. Location, field management, and cover crop interseeding information for on-farm experiments conducted in Michigan in 2017 and 2018.

Location	Year	Lat./Long.	Soil Type	pH	SOM	Till	Corn planted	Rate[c]	V3	V6	AR[a]	CC[a]	OR[a]
Springport	‘17	42° 14’ 53” N 84° 24’ 19” W	Riddles Sandy Loam	5.9	1.6	No	31 May	83,980	19 Jun	27 Jun	16.8	22.4	11.2
Hickory Corners[b] A	‘17	42° 24’ 35” N 85° 22’ 07” W	Kalamazoo Loam	6.6	2.0	No	8 May	71,630	1 Jun	19 Jun	33.6	33.6	22.4
Hickory Corners B	‘17	42° 24’ 35” N 85° 22’ 07” W	Kalamazoo Loam	5.9	1.8	Yes	28 Apr	69,160	1 Jun	19 Jun	33.6	33.6	22.4
Clayton	‘17	41° 51’ 25” N 84° 14’ 18” W	Glynwood Loam	7.2	3.2	No	13 May	79,100	17 Jun	28 Jun	24.7	13.5	6.7
Hillman	‘17	45° 03’ 40” N 83° 54’ 02” W	Negwegon Silt Loam	-	-	Yes	14 May	79,100	14 Jun	5 Jul	16.8	22.4	11.2
Hart	‘17	43° 42’ 06” N 86° 20’ 32” W	Spinks-Tekenink Loamy Sand	6.6	1.5	Yes	13 May	70,395	5 Jun	16 Jun	16.8	22.4	11.2
Springport	‘18	42° 14’ 53” N 84° 24’ 19” W	Hillsdale Riddles Sandy Loam	6.2	1.8	No	25 May	74,100	16 Jun	21 Jun	8.4	11.2	7.2
Hickory Corners	‘18	42° 24’ 35” N 85° 22’ 07” W	Kalamazoo Loam	6.6	2.0	No	2 May	69,160	1 Jun	14 Jun	16.8	22.4	11.2
Hillman	‘18	45° 03’ 40” N 83° 54’ 02” W	Algonquin-Springport Complex	7.7	-	Yes	17 May	80,275	7 Jun	28 Jun	16.8	22.4	11.2

Table 7.01 (cont'd)

[a]AR=annual ryegrass; CC=crimson clover; OR=oilseed radish; kg ha^{-1}.

[b]Hickory Corners is the location of the Michigan State University Kellogg Biological Station.

[c]Corn planting population.

Table 7.02. Cumulative growing season and interseeding period[a] precipitation for each site and year for cover crops interseeded in corn at on-farm locations in Michigan in 2017 and 2018.

		Cumulative Precipitation (April 1-Oct. 30)	Cumulative Precipitation Interseeding Period[a]
Site	Year	--------mm--------	--------mm--------
Springport	2017	565	88
Hickory Corners[b] A	2017	628	120
Hickory Corners B	2017	628	120
Clayton	2017	466	140
Hillman	2017	519	151
Hart	2017	643	141
Springport	2018	553	70
Hickory Corners	2018	641	146
Hillman	2018	395	55

[a]Interseeding period was from 7 days prior to the V3 interseeding until 30 days after the V6 interseeding timing

[b]Hickory Corners is the location of the Michigan State University Kellogg Biological Station.

Table 7.03. Cover crop percent emergence 30 days after interseeding at each location and year for cover crop species combined over interseeding timings and each interseeding timing combined over cover crop species.

	2017						2018		
	Clayton	Hillman	Springport	Hickory Corners A	Hickory Corners B	Hart	Hillman[a]	Springport	Hickory Corners
Cover crop	% Emergence[b]						% Emergence		
annual ryegrass	3 b[c]	17 ab	6 b	3 b	12 a	9 ab	20 b	1 b	4 b
crimson clover	4 b	13 b	3 b	3 b	5 b	3 b	23 b	2 b	3 b
oilseed radish	15 a	24 a	18 a	12 a	12 a	15 a	62 a	16 a	21 a
±SEM	±2	±2	±2	± 1	±1	±3	±6	±2	±3
Interseeding Time	% Emergence						% Emergence		
V3	8 a	21 a	7 a	7 a	13 a	9 a	-	10 a	12 a
V6	6 a	16 a	11 a	5 a	6 b	6 a	-	3 b	6 a
±SEM[d]	±2	±2	±2	±1	±1	±2	-	±1	±3

[a]Cover crops seeded at V3 at the ‘N’ site in 2018 had not emerged by 30 days after interseeding.
[b]Emergence as a percent of the seeded rate.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher’s LSD.
[d]Standard error of mean for LSD comparisons.

Table 7.04. Cover crop percent emergence in October prior to corn harvest at each location and year for cover crop species combined over interseeding timings and each interseeding timing combined over cover crop species.

	2017						2018		
	Clayton	Hillman[a]	Springport	Hickory Corners A	Hickory Corners B	Hart	Hillman	Springport	Hickory Corners
Cover crop			% Emergence[b]					% Emergence	
annual ryegrass	7 a[c]	-	8 b	3 b	10 b	7 b	23 a	2 b	<1 b
crimson clover	3 a	-	2 c	3 b	4 c	2 b	32 a	<1 b	<1 b
oilseed radish	17 a	-	17 a	14 a	15 a	13 a	10 b	15 a	16 a
±SEM	±4	-	±2	± 2	±1	±2	±4	±2	±3
Interseeding Time			% Emergence					% Emergence	
V3	9 a	-	8 a	7 a	12 a	9 a	18 a	7 a	8 a
V6	9 a	-	10 a	6 a	7 b	6 a	25 a	4 a	3 a
±SEM[d]	±4	-	±2	±1	±1	±2	±4	±1	±3

[a]Cover crop density was not recorded at the Hillman site.
[b]Emergence as a percent of the seeded rate.
[c]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[d]Standard error of mean for LSD comparisons.

Table 7.05. Cover crop density 30 days after interseeding at each location and year comparing cover crop species and interseeding timings.

	2017						2018		
	Clayton	Hillman	Springport	Hickory Corners A	Hickory Corners B	Hart	Hillman[a]	Springport	Hickory Corners
Cover crop	plants m^{-2}						plants m^{-2}		
annual ryegrass	35 a[b]	146 a	52 a	47 a	201 a	77 a	166 a	3 b	29 a
crimson clover	25 a	92 b	20 b	33 a	56 b	23 b	105 ab	4 b	19 a
oilseed radish	20 a	21 c	16 b	21 a	20 b	13 b	52 b	9 a	18 a
±SEM	±9	±13	±5	±16	±16	±7	±16	±1	±8
Interseeding Time	plants m^{-2}						plants m^{-2}		
V3	21 a	66 b	27 a	43 a	113 a	48 a	-	8 a	28 a
V6	32 a	106 a	31 a	24 a	72 b	27 b	-	2 b	10 b
±SEM[c]	±8	±11	±4	±13	±13	±6	-	±1	±6

[a]Cover crops seeded at V3 at the 'N' site in 2018 had not emerged by 30 days after interseeding.
[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[c]Standard error of mean for LSD comparisons.

Table 7.06. Cover crop density in October at each location and year comparing cover crop species and interseeding timings

	2017						2018		
	Clayton	Hillman[a]	Springport	Hickory Corners A	Hickory Corners B	Hart	Hillman	Springport	Hickory Corners
Cover crop	plants m^{-2}						plants m^{-2}		
annual ryegrass	62 a[b]	-	69 a	44 a	173 a	55 a	188 a	5 a	1 b
crimson clover	22 ab	-	12 b	34 a	40 b	12 b	42 b	<1 a	3 b
oilseed radish	15 b	-	15 b	24 a	25 b	12 b	25 b	8 a	14 a
±SEM	±13	-	±9	± 17	±14	±6	±26	±3	±3
Interseeding Time	plants m^{-2}						plants m^{-2}		
V3	35 a	-	26 a	37 a	93 a	36 a	82 a	4 a	6 a
V6	30 a	-	38 a	31 a	66 a	16 b	87 a	6 a	3 a
±SEM[c]	±9	-	±8	±16	±12	±5	±22	±2	±2

[a]Cover crop density was not recorded at the Hillman site.
[b]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[c]Standard error of mean for LSD comparisons.

Table 7.07. Cover crop density 30 days after interseeding (DAI) and in October (Harvest), and cover crop biomass in October combined over interseeding timings comparing tilled fields with no-till fields.

	Annual ryegrass		Crimson clover		Oilseed radish	
	30 DAI	Harvest	30 DAI	Harvest	30 DAI	Harvest
Tillage	plants m^{-2}					
Tilled	157 a[a]	181 a	83 a	32 a	26 a	25 a
No-till	38 b	35 b	23 b	16 a	15 a	13 a
±SEM	±12	±16	±16	±8	±8	±8
Tillage	kg ha^{-1}					
Tilled	366 a		334 a		479 a	
No-till	64 b		47 b		246 b	
±SEM[b]	±68		±67		±76	

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 7.08. Cover crop biomass in October prior to corn harvest at each location and year for cover crop species combined over interseeding timings and each interseeding timing combined over cover crop species.

	2017						2018		
Cover crop	Clayton	Hillman	Springport	Hickory Corners A	Hickory Corners B	Hart	Hillman	Springport	Hickory Corners
	kg ha^{-1}						kg ha^{-1}		
annual ryegrass	56 a[a]	612 a	44 b	35 b	241 b	202 ab	248 a	8 b	<1 b
crimson clover	11 a	539 a	16 b	152 b	196 b	40 b	46 b	0 b	25 b
oilseed radish	63 a	709 a	262 a	436 a	1103 a	456 a	261 a	108 a	259 a
±SEM[b]	±18	±167	± 54	±96	±164	±97	±44	±15	±52
Interseeding Time	kg ha^{-1}						kg ha^{-1}		
V3	27 a	550 a	201 a	255 a	824 a	270 a	188 a	45 a	152 a
V6	60 a	689 a	13 b	161 a	202 b	189 a	182 a	33 a	37 b
±SEM	±14	±153	±44	±77	±139	±79	±40	±12	±46

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 7.09. Corn grain yield at each location and year for each combination of cover crop species and interseeding timing compared with the no cover crop control.

Species and Interseeding Timing	2017 Clayton	2017 Hillman	2017 Springport	2017 Hickory Corners A	2017 Hickory Corners B	2017 Hart	2018 Hillman	2018 Springport	2018 Hickory Corners
	Mg ha^{-1}						Mg ha^{-1}		
annual ryegrass V3	12.0 bc[a]	7.7 a	10.6 a	9.5 a	8.7 a	12.4 a	9.4 a	11.0 a	8.1 a
annual ryegrass V6	11.4 cd	7.7 a	10.7 a	9.5 a	8.7 a	11.4 a	9.0 a	11.5 a	8.9 a
crimson clover V3	12.3 ab	9.1 a	10.7 a	9.3 a	8.8 a	12.3 a	9.2 a	11.5 a	7.9 a
crimson clover V6	12.0 bc	8.3 a	10.9 a	8.8 a	9.1 a	11.4 a	9.7 a	11.5 a	8.8 a
oilseed radish V3	12.8 a	8.0 a	10.7 a	9.1 a	8.5 a	11.7 a	9.3 a	11.2 a	8.0 a
oilseed radish V6	11.1 d	7.7 a	10.9 a	9.7 a	8.9 a	11.1 a	9.3 a	11.4 a	8.7 a
No Cover	11.9 bc	7.7 a	-[b]	9.5 a	8.7 a	11.2 a	9.3 a	11.2 a	8.7 a
±SEM	±0.2	±0.4	±0.1	±0.3	±0.3	±0.4	±0.3	±0.3 a	±0.4

[a]Within columns, means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Farmer did not harvest no cover control strips.
[c]Standard error of mean for LSD comparisons.

Table 7.10. Remotely sensed canopy temperature at the Hickory Corners A 2017 site comparing interseeding timings at each flyover date.

	Interseeding Timing	
Date	V3	V6
	Temperature °C	
29 May	13.74 k[a]	13.69 k
16 June	27.63 b	28.23 a
28 June	22.62 g	22.71 fg
6 July	27.18 c	27.56 b
18 July	24.44 e	24.76 c
31 July	22.75 fg	22.89 f
20 August	21.43 i	21.28 i
6 September	15.04 j	15.02 j
20 September	21.78 h	21.96 h
±SEM[b]	±0.09	

[a]Means with the same letter are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.
[b]Standard error of mean for LSD comparisons.

Table 7.11. Correlation between canopy temperature and corn grain yield and cover crop biomass for each flyover date for the Hickory Corners A 2017 location (n=24 for each date). Corn grain yield ranged from 8.4-10.4 Mg ha^{-1}.

		Corn grain yield			Cover crop biomass		
Date	Range °C	Slope	R^2	*p* value[a]	Slope	R^2	*p* value[a]
		Mg ha^{-1}/°C			kg ha^{-1}/°C		
29 May	13.6-13.9	-0.21	<0.01	0.8609	588	0.06	0.2656
16 June	24.9-29.2	0.10	0.03	0.4285	-28	0.01	0.6016
28 June	22.4-23.1	-0.74	0.06	0.2393	-368	0.10	0.1414
6 July	26.9-28.7	-0.52	0.14	0.0774	-192	0.12	0.1127
18 July	24.9-25.1	0.08	<0.01	0.8776	-368	0.19	0.0412
31 July	22.3-23.1	0.84	0.10	0.1258	45	<0.01	0.8588
20 August	20.6-21.7	-0.01	0.00	0.9857	192	0.04	0.3650
6 September	14.6-15.5	0.08	<0.01	0.2363	56	<0.01	0.7736
20 September	21.2-22.2	0.58	0.17	0.044	-113	0.04	0.3686

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.

Table 7.12. Correlation between canopy temperature and corn grain yield and cover crop biomass for each flyover date for the Springport 2017 location (n=6 for each date). Corn grain yield ranged from 9.9-10.1 Mg ha^{-1}.

		Corn grain yield			Cover crop biomass		
Date	Range °C	Slope	R^2	*p* value[a]	Slope	R^2	*p* value[a]
		Mg ha^{-1}/°C			kg ha^{-1}/°C		
12 April	22.5-22.8	0.11	0.01	0.8189	1575	0.65	0.052
8 May	8.6-8.9	0.16	0.11	0.5118	-621	0.34	0.2272
29 May	23.8-24.1	-0.41	0.33	0.2337	-469	0.09	0.5675
15 June	25.5-25.9	-0.41	0.87	0.0064	454	0.22	0.3515
29 June	20.7-20.9	-1.11	0.63	0.0606	1862	0.37	0.204
6 July	34.8-35.7	0.01	<0.01	0.9311	-180	0.08	0.5757
18 July	23.6-23.8	-0.59	0.08	0.5814	-327	0.01	0.8918
31 July	27.1-27.5	-0.44	0.56	0.0891	-268	0.04	0.6951
19 August	21.8-21.9	0.05	0.00	0.9469	-2459	0.52	0.1082
5 September	15.5-15.7	0.12	0.01	0.8393	541	0.05	0.6838
20 September	21.3-21.4	-0.26	0.01	0.8733	-82	<0.01	0.9817

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.

Table 7.13. Correlation between canopy temperature and corn grain yield and cover crop biomass for each flyover date for the Hickory Corners B 2017 location (n=56 for each date). Corn grain yield ranged from 6.3 to 8.2 Mg ha^{-1}.

		Corn grain yield			Cover crop biomass		
Date	Range °C	Slope	R^2	*p* value[a]	Slope	R^2	*p* value[a]
		Mg ha^{-1}/°C			kg ha^{-1}/°C		
12 April	20.5-21.6	-0.67	0.23	0.0006	-297	0.02	0.3253
8 May	8.5-9.1	-0.15	0.01	0.5275	366	0.02	0.2933
29 May	13.7-14.3	0.22	0.01	0.5042	-651	0.03	0.206
16 June	25.1-26.7	-0.44	0.14	0.0093	-607	0.11	0.011
28 June	16.7-17.8	-0.29	0.04	0.1889	106	<0.01	0.7712
6 July	27.8-30.7	-0.13	0.04	0.1485	-68	<0.01	0.6733
18 July	13.5-21.1	0.11	0.11	0.0237	-106	0.07	0.0487
31 July	23.2-24.5	-0.60	0.22	0.0007	-580	0.09	0.0278
20 August	22.8-23.6	-1.33	0.53	0.0001	-810	0.07	0.0561
6 September	10.2-12.3	-0.25	0.07	0.0748	219	0.07	0.0466
20 September	22.8-23.0	-2.86	0.12	0.0172	-3285	0.06	0.0741

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.

Table 7.14. Correlation between canopy temperature and corn grain yield and cover crop biomass for each flyover date for the Hart 2017 location (n=24 for each date). Corn grain yield ranged from 9.8-13.2 Mg ha^{-1}.

		Corn grain yield			Cover crop biomass		
Date	Range °C	Slope	R^2	*p* value[a]	Slope	R^2	*p* value[a]
		Mg ha^{-1}/°C			kg ha^{-1}/°C		
30 May	20.0-24.9	0.30	0.19	0.035	-45	0.03	0.3693
16 June	28.0-30.1	0.67	0.17	0.0422	-86	0.02	0.4644
27 June	17.9-19.8	0.70	0.10	0.1268	-97	0.02	0.5437
7 July	24.0-25.4	0.51	0.05	0.2997	-212	0.07	0.2022
17 July	19.3-20.9	0.81	0.15	0.0591	-151	0.50	0.3191
1 August	22.7-23.5	-0.15	<0.01	0.8607	-475	0.12	0.0981
20 August	20.4-21.3	1.29	0.17	0.0489	-296	0.05	0.2855
6 September	12.0-12.3	-0.62	0.01	0.6955	-776	0.10	0.141
21 September	26.6-28.0	-0.10	<0.01	0.8021	-323	0.22	0.0204

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.

Table 7.15. Correlation between canopy temperature and corn grain yield and cover crop biomass for each flyover date for the Springport 2018 location (n=8 for each date). Corn grain yield ranged from 10.8-11.4 Mg ha^{-1}.

		Corn grain yield			Cover crop biomass		
Date	Range °C	Slope	R^2	*p* value[a]	Slope	R^2	*p* value[a]
		Mg ha^{-1}/°C			kg ha^{-1}/°C		
7 May	32.8-33.6	0.50	0.32	0.1461	-139	0.04	0.6869
23 May	22.1-22.5	0.98	0.45	0.0691	48	0.02	0.8154
6 June	26.2-26.8	0.57	0.25	0.2067	36	0.01	0.8723
18 June	29.5-30.1	0.87	0.73	0.0069	32	0.01	0.8421
1 July	31.2-32.0	0.41	0.30	0.1586	-4	<0.01	0.9697
8 July	33.2-34.7	-0.01	<0.01	0.9492	21	0.05	0.6656
17 July	29.0-29.8	0.15	0.05	0.5928	18	0.02	0.8107
3 August	23.5-23.6	0.89	0.03	0.6893	-229	0.04	0.7223
22 August	19.3-19.5	0.37	0.01	0.8013	-162	0.04	0.6991
14 September	22.6-22.8	-0.57	0.05	0.5766	-82	0.02	0.8081
4 October	17.5-18.0	-0.77	0.42	0.0833	-136	0.24	0.3214
16 October	13.5-13.7	-3.04	0.85	0.0011	184	0.03	0.7598

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.

Table 7.16. Correlation between canopy temperature and corn grain yield and cover crop biomass for each flyover date for the Hickory Corners 2018 location (n=21 for each date). Corn grain yield ranged from 7.0-9.6 Mg ha^{-1}.

		Corn grain yield			Cover crop biomass		
Date	Range	Slope	R^2	*p* value[a]	Slope	R^2	*p* value[a]
	°C	Mg ha^{-1}/°C			kg ha^{-1}/°C		
5 August	30.7-31.2	-1.26	0.08	0.2179	-161	0.01	0.7047
22 August	16.9-18.2	-2.01	0.16	0.0723	-61	<0.01	0.9024
4 September	25.4-26.3	-2.68	0.19	0.0500	-266	0.01	0.6582
4 October	15.8-17.3	-0.52	0.07	0.2577	92	0.01	0.6415
16 October	11.6-12.4	-2.57	0.49	0.0004	334	0.03	0.4648

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.

Table 7.17. Correlation between cover crop biomass and remotely sensed canopy temperature for each measurement date combined over sites within each year.

Date	Range °C	Slope	Cover crop biomass R^2	*p* value[a]
2017		-------kg ha^{-1}/°C-------		
12 April[b]	20.5-22.8	-232	0.05	0.1028
8 May[b]	8.5-9.1	867	0.10	0.2584
29-30 May	13.6-24.9	-28	0.04	0.0696
15-16 June	24.9-30.1	-102	0.08	0.0048
27-29 June	16.7-23.1	-65	0.07	0.0117
6-7 July	24.0-35.7	11.3	<0.01	0.7532
17-18 July	12.8-25.1	-63.0	0.13	0.0005
31 Jul-1 Aug	22.4-27.5	-26	<0.01	0.5018
19-20 August	20.4-23.7	129	0.06	0.0309
5-6 September	10.2-15.7	-71	0.05	0.1584
20-21 September	21.2-28.0	-22	0.01	0.4905
2018				
3/5 August	23.5-31.3	7	0.01	0.5872
22 August	16.9-19.5	-27	0.01	0.6791
4 October	15.8-18.0	-16	<0.01	0.8139
16 October	11.6-13.7	-20	<0.01	0.7467

[a]Slope of the regression equation is different from zero if *p*-value is <0.05.
[b]Only Springport 2017 and Hickory Corners B 2017 had data collected on this date.

Figure 7.01. 2017 (1) and 2018 (2) cover crop biomass by location. Each circle represents the average combined biomass of annual ryegrass, crimson clover, and oilseed radish. The size of each circle is proportional to the amount of biomass produced compared with the highest-producing site (B – 1859 kg ha^{-1}). Within each circle, the average amount of biomass produced by annual ryegrass (white), crimson clover (gray), and oilseed radish (black) is shown. 2017: A – Clayton; B – Hillman; C – Springport; D – Hickory Corners A; E – Hickory Corners B; F – Hart. 2018: G – Hillman; H – Springport; I – Hickory Corners.

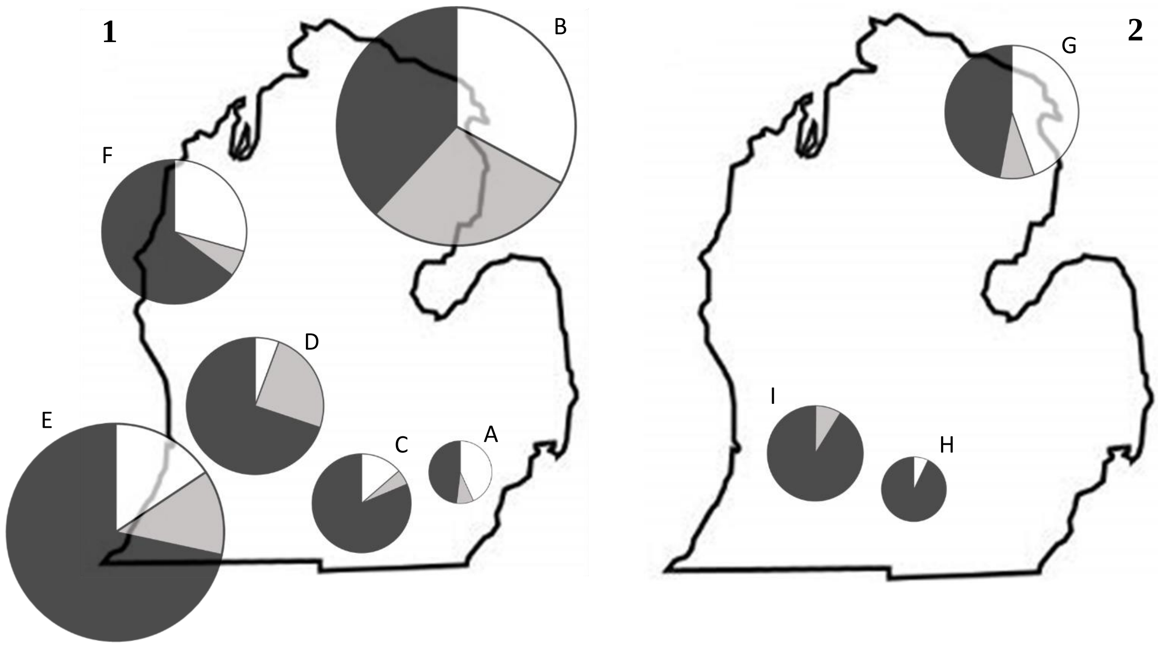


Figure 7.02. Correlation between fall annual ryegrass density and biomass combined over all site years.

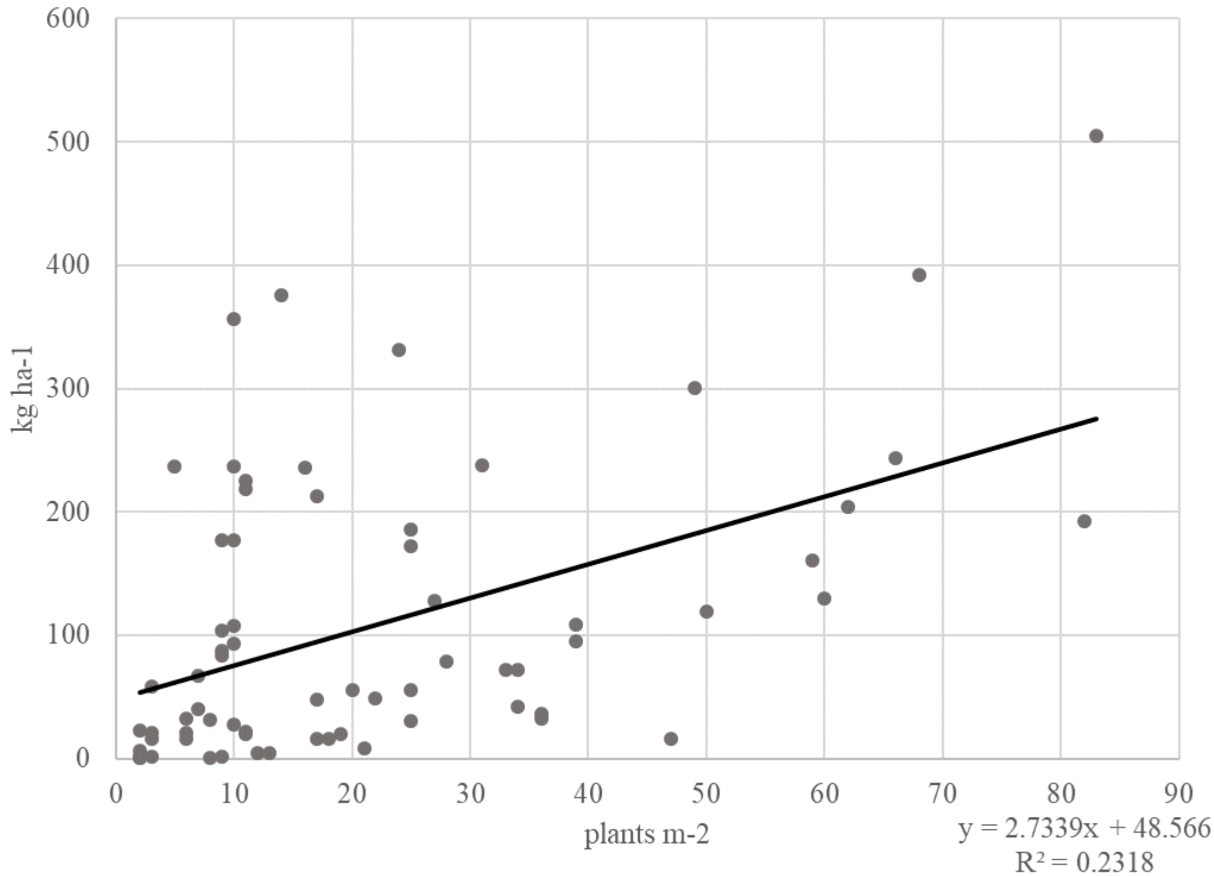


Figure 7.03. Correlation between fall crimson clover density and biomass combined over all site years.

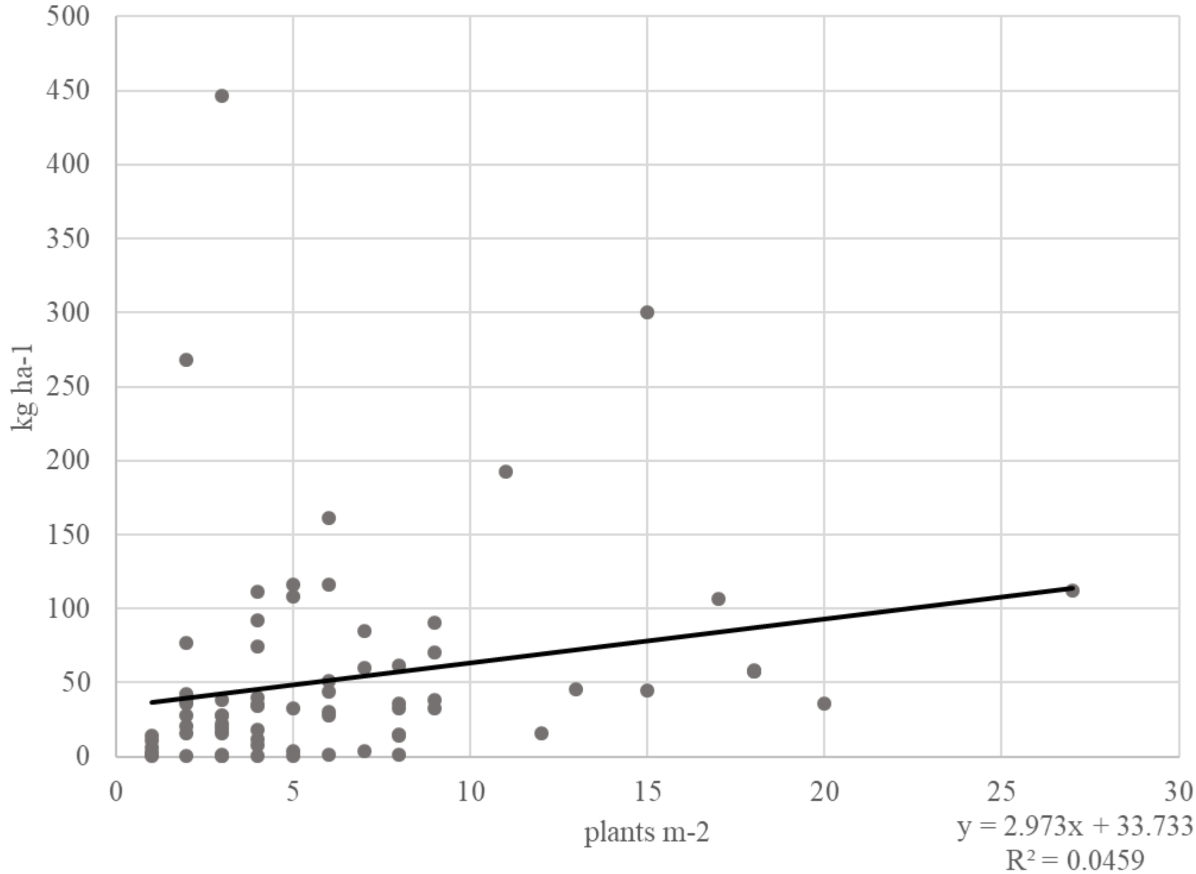


Figure 7.04. Correlation between fall oilseed radish density and biomass combined over all site years.

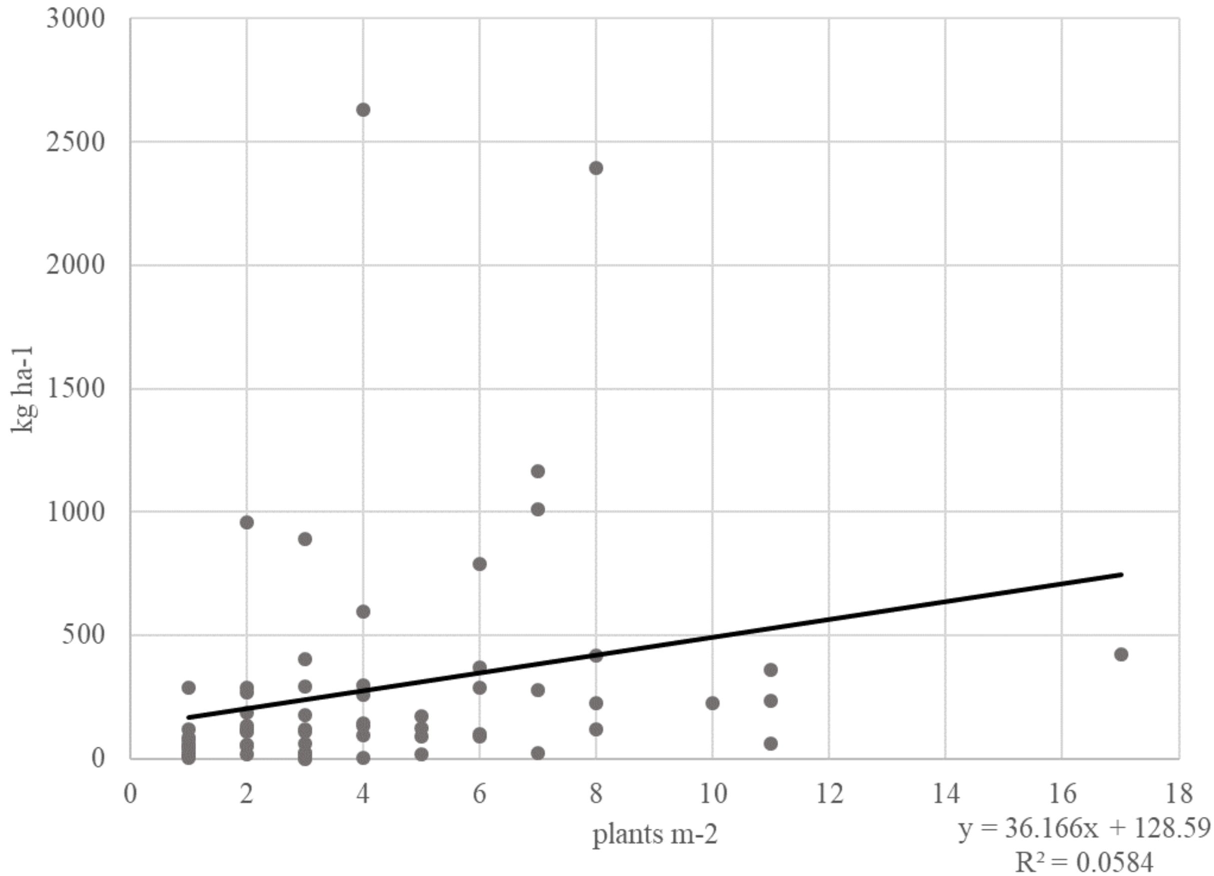


Figure 7.05. Correlation between corn grain yield and remotely sensed canopy temperature combined over all site years; *p*-value = 0.7601.

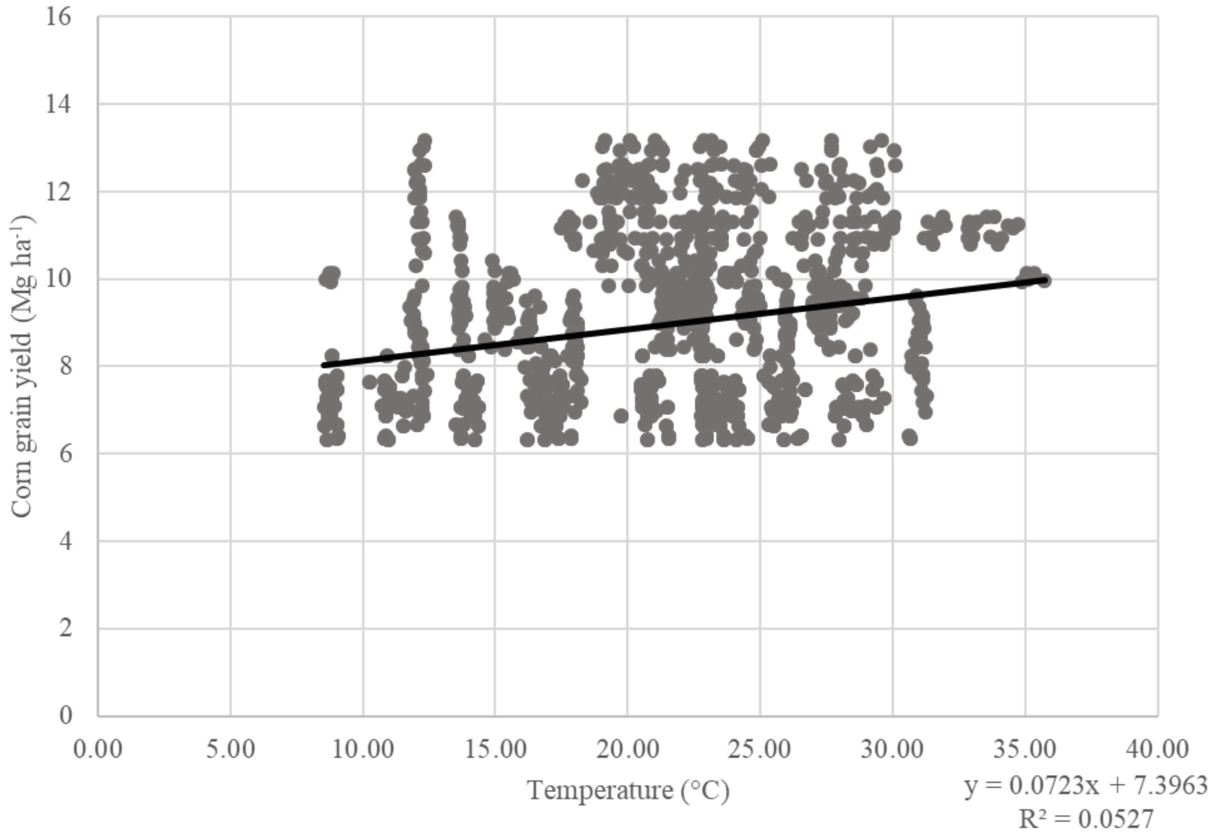


Figure 7.06. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 12 April (Springport 2017; Hickory Corners B 2017); *p*-value = <0.0001.

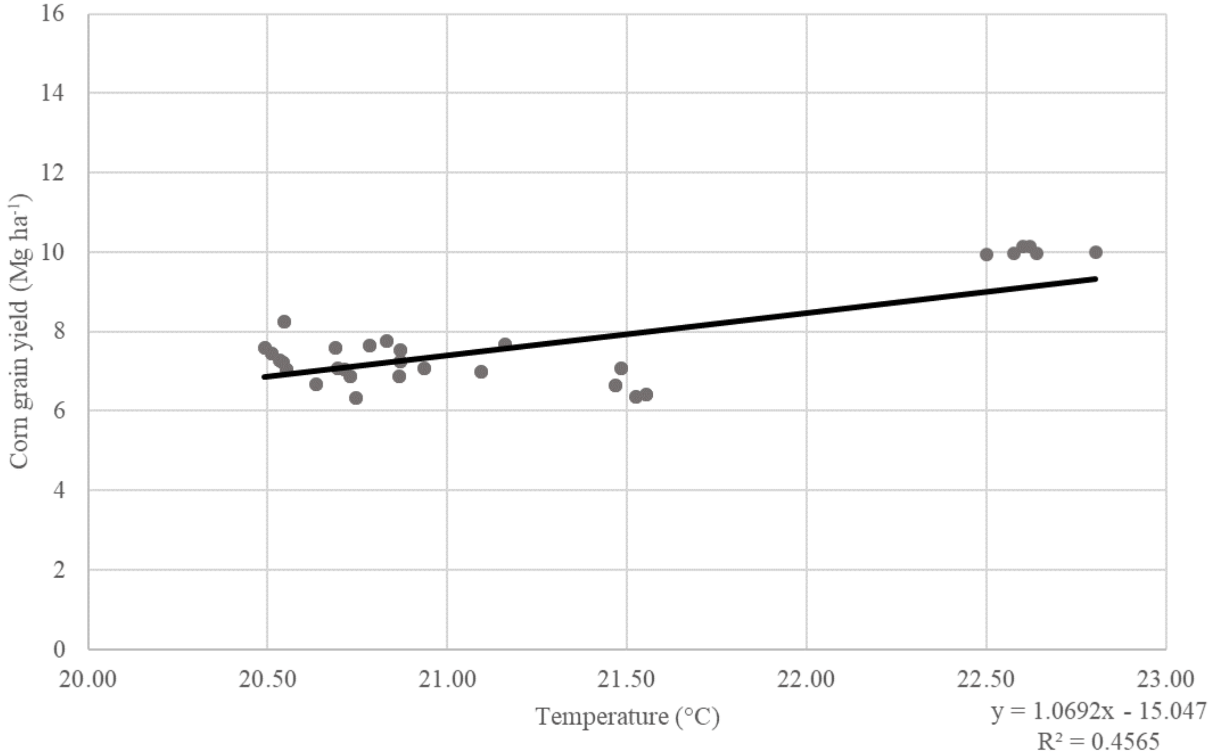


Figure 7.07. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 8 May (Springport 2017; Hickory Corners B 2017); *p*-value = 0.3771.

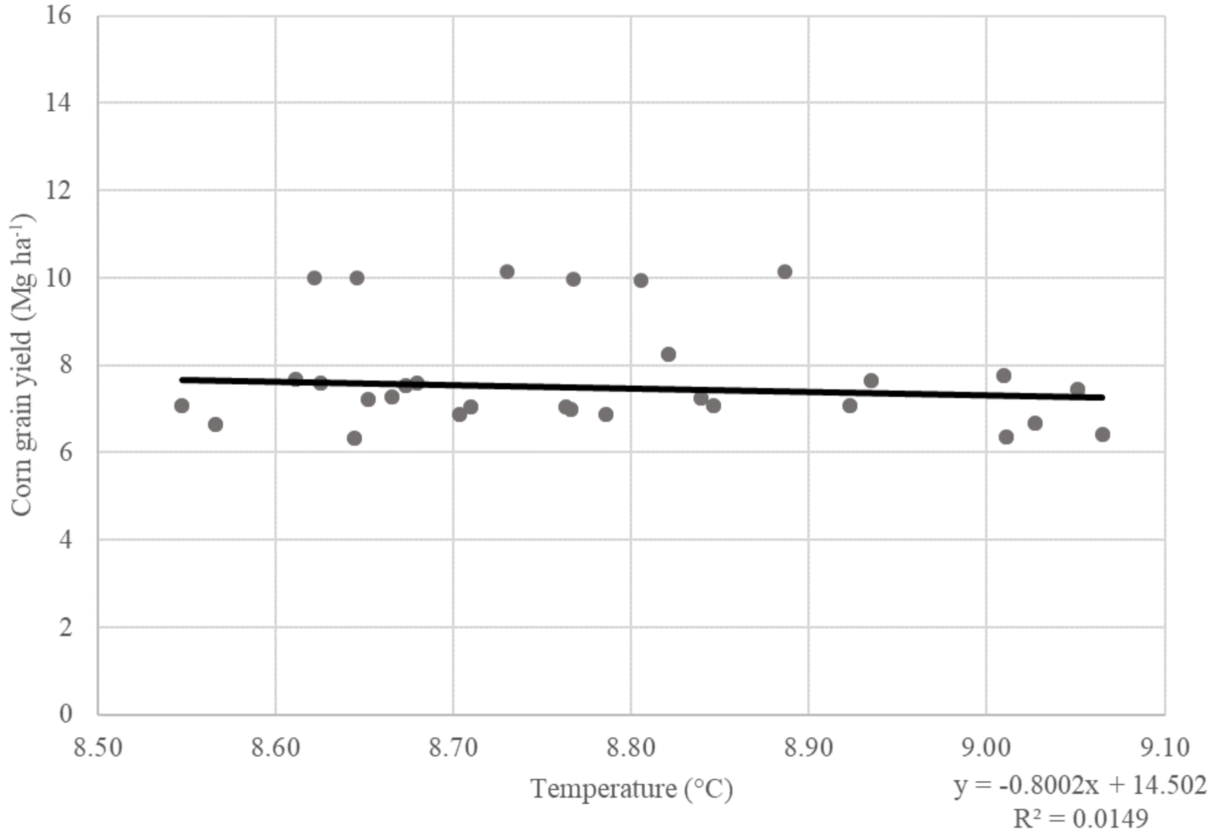


Figure 7.08. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 29-30 May (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

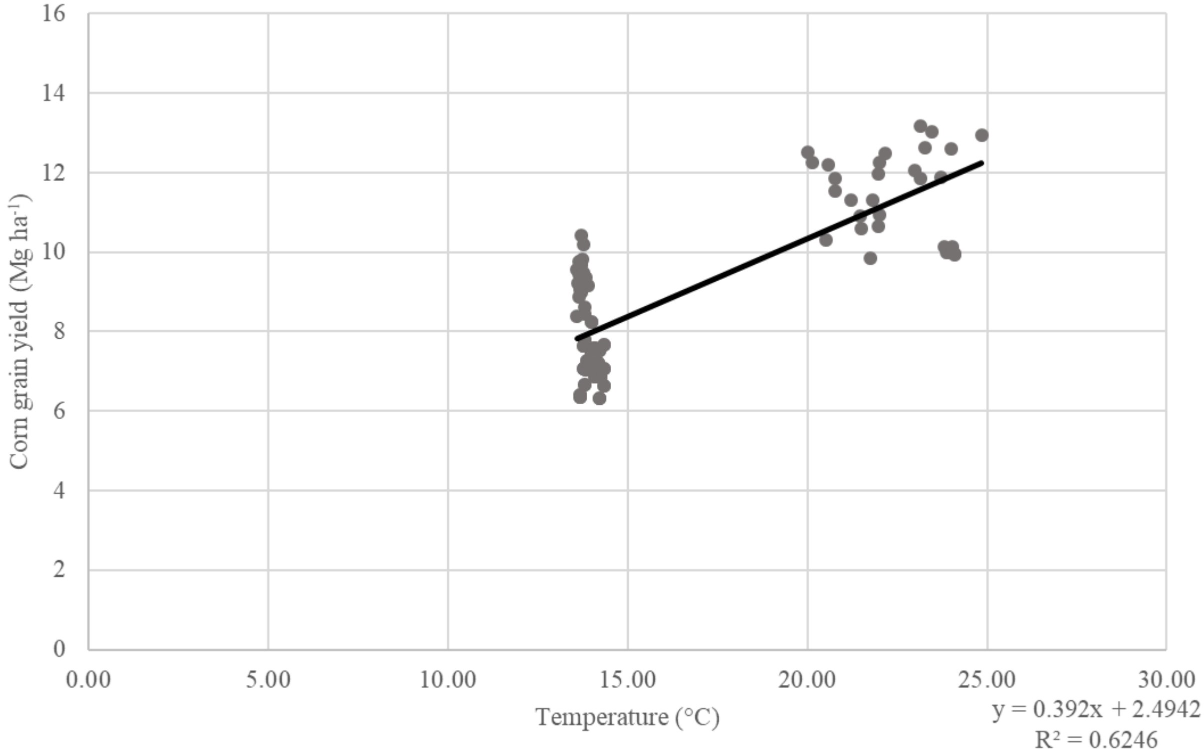


Figure 7.09. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 15-16 June (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

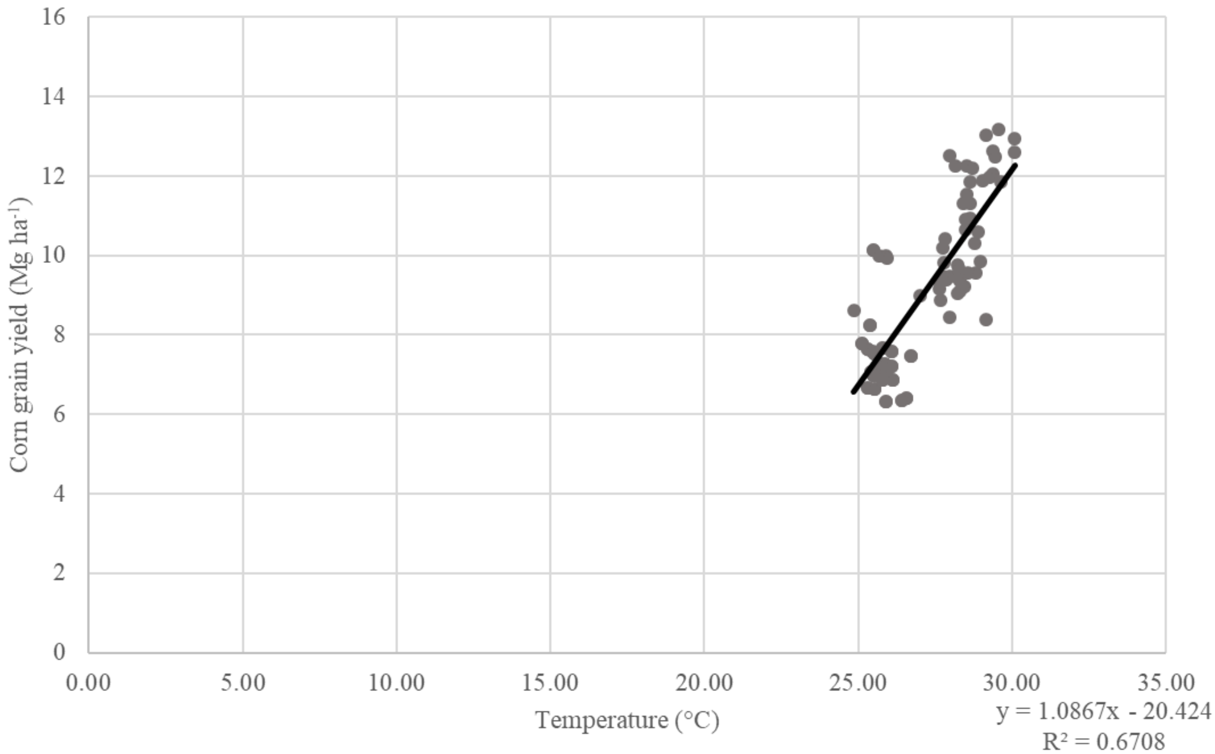


Figure 7.10. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 27-29 June (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

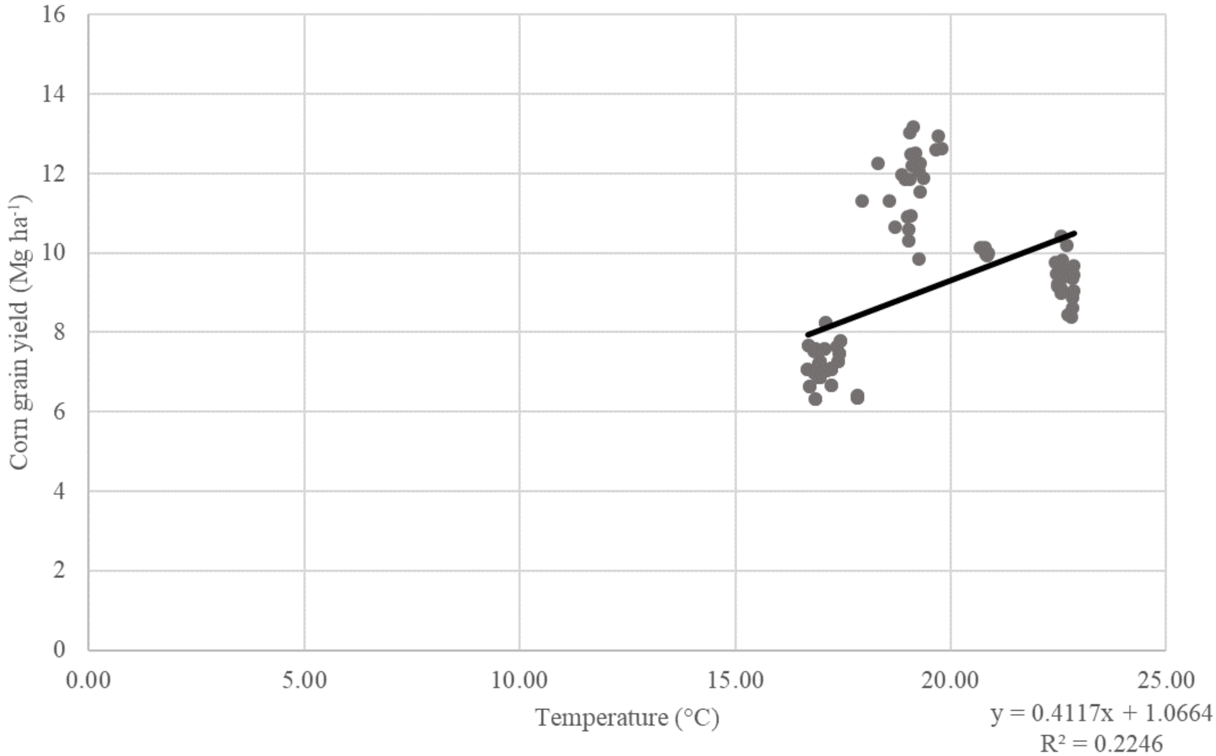


Figure 7.11. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 6-7 July (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

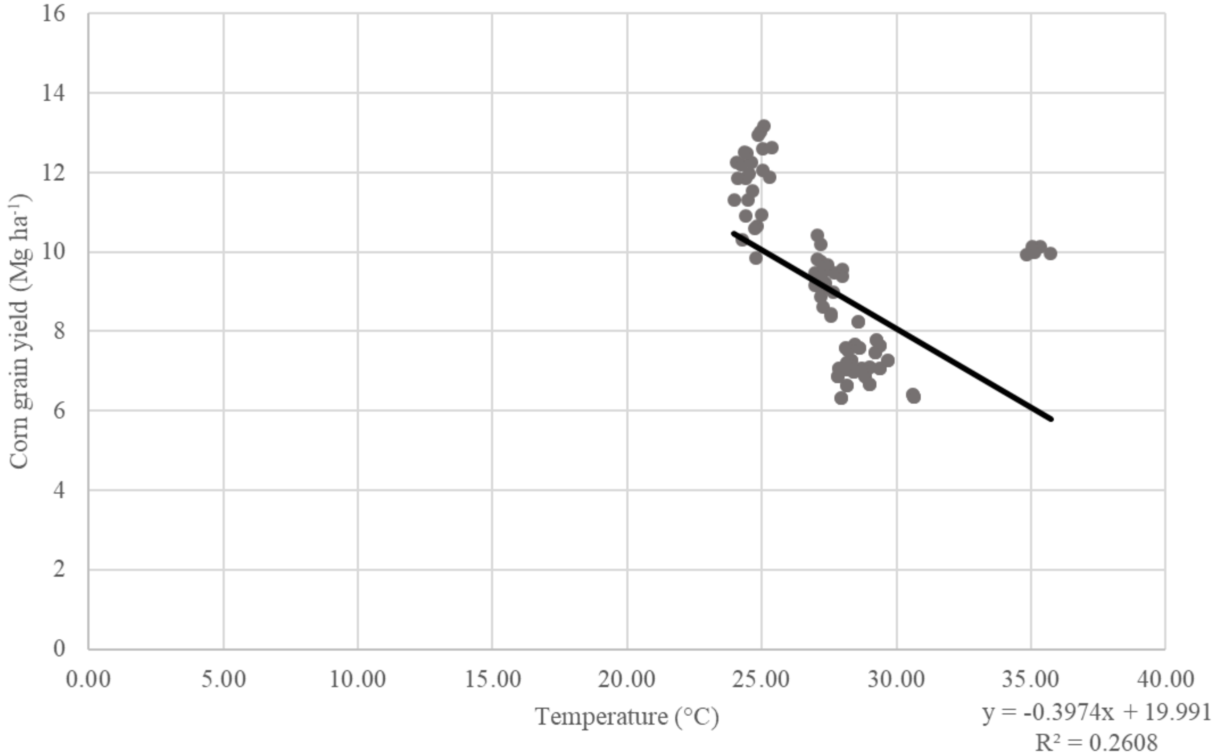


Figure 7.12. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 17-18 July (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

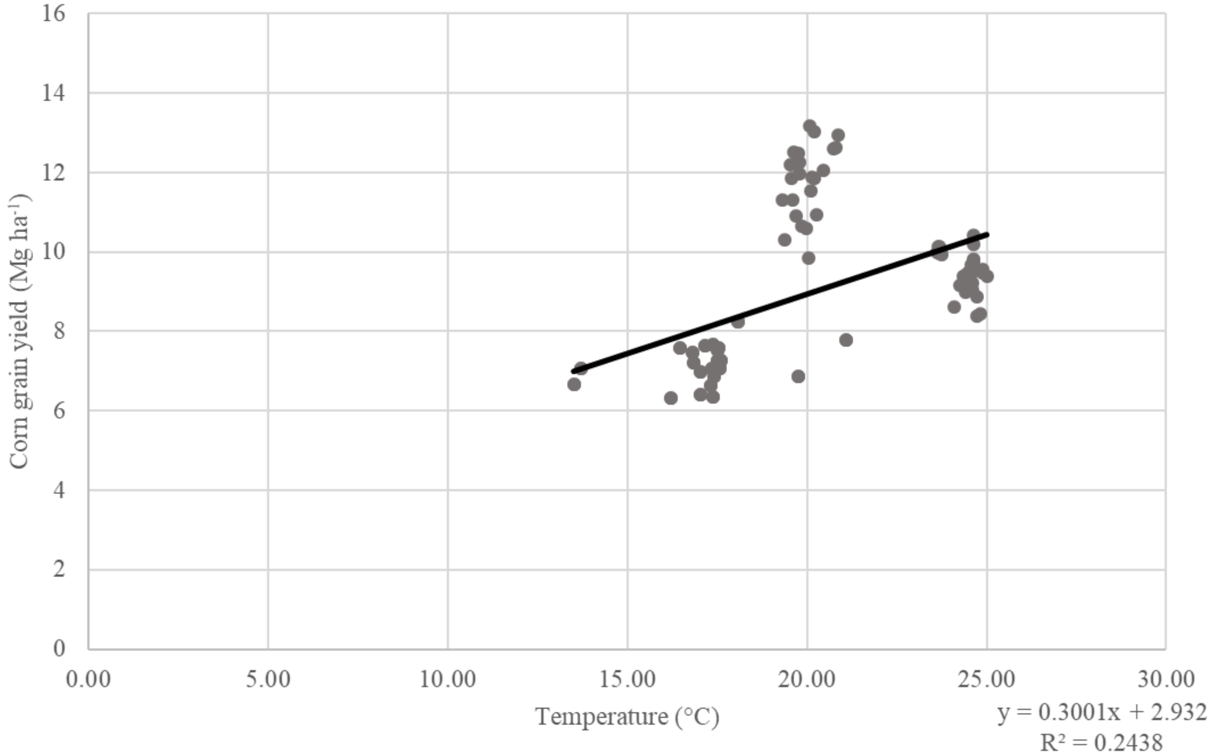


Figure 7.13. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 31 July – 1 August (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = 0.0341.

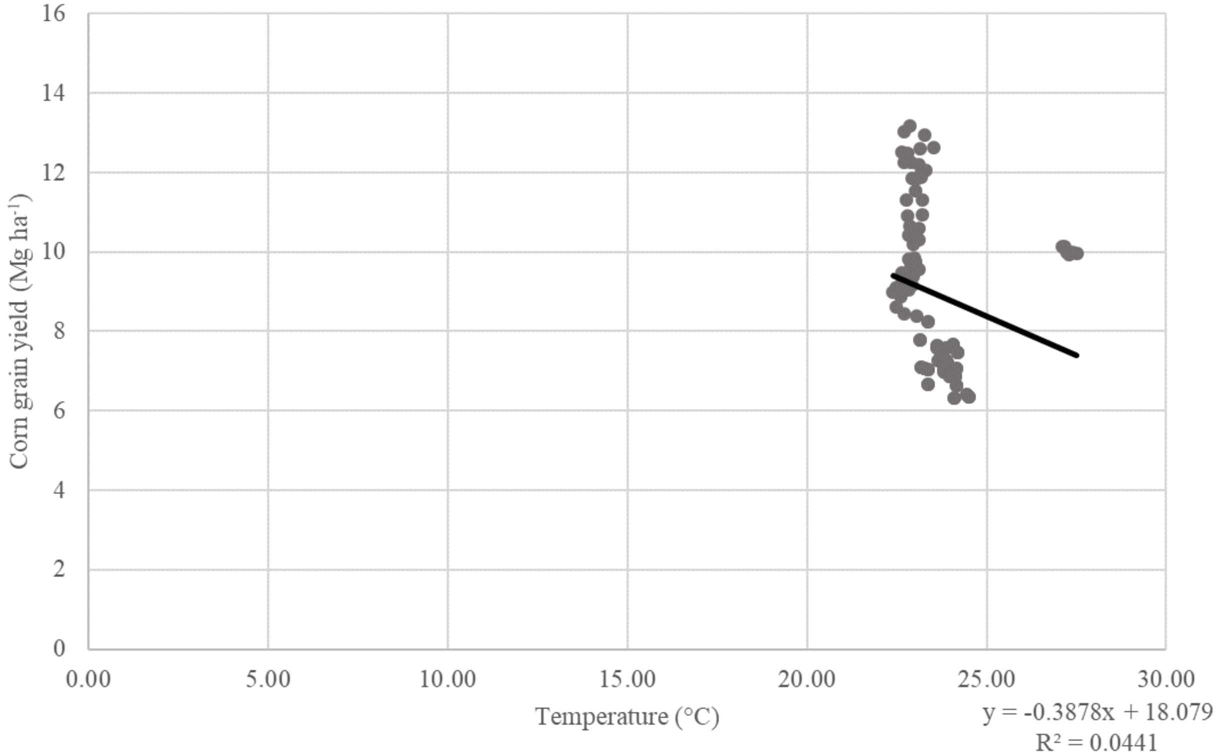


Figure 7.14. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 19-20 August (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

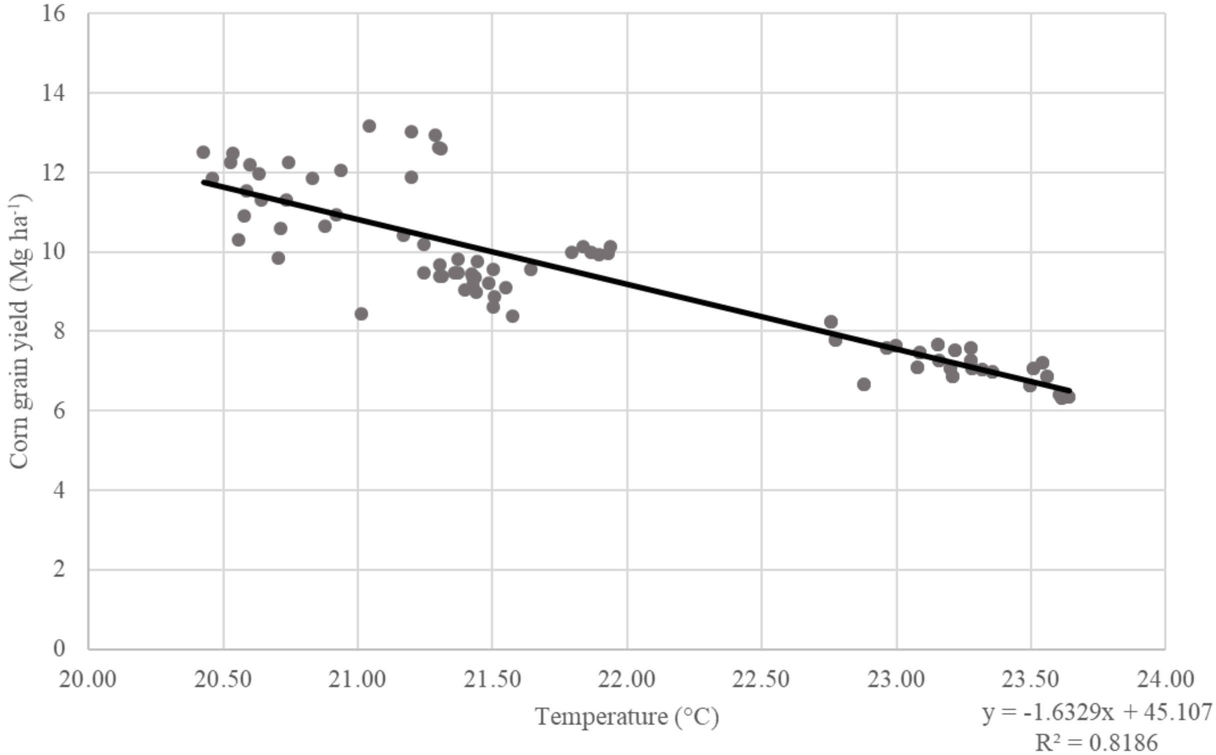


Figure 7.15. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 5-6 September (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

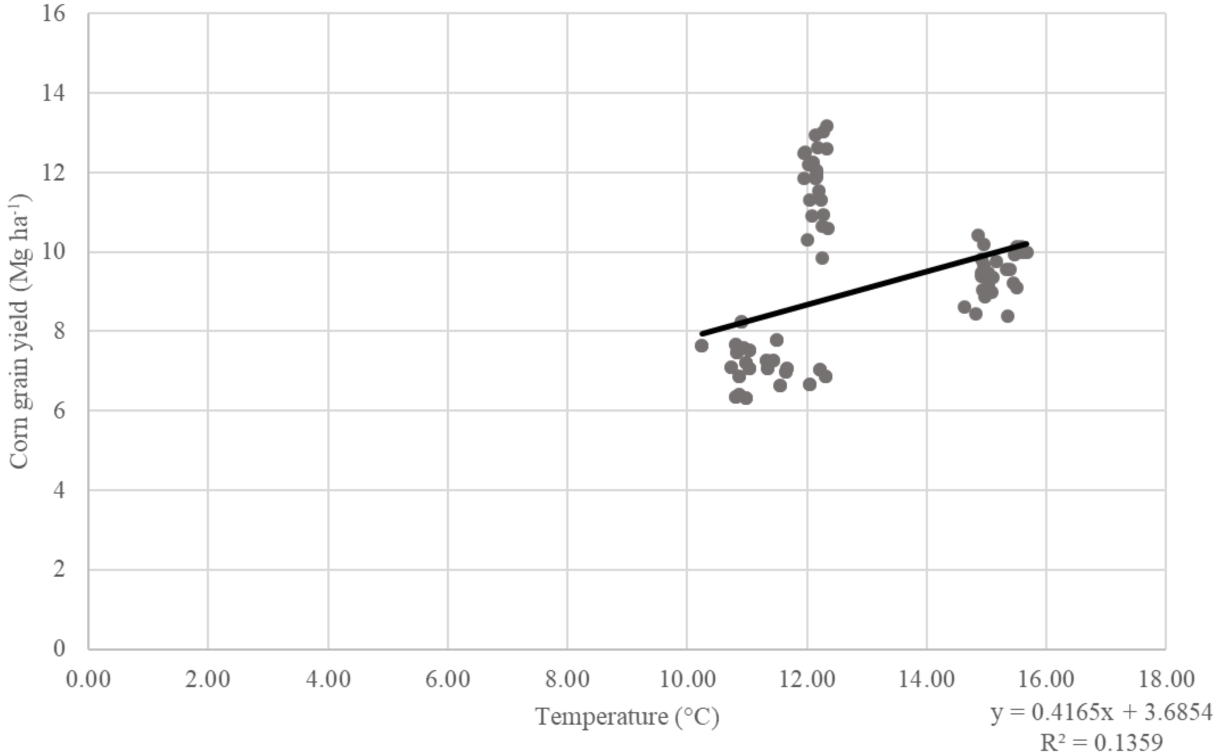


Figure 7.16. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 20-21 September (Springport 2017; Hickory Corners A 2017; Hickory Corners B 2017; Hart 2017); *p*-value = <0.0001.

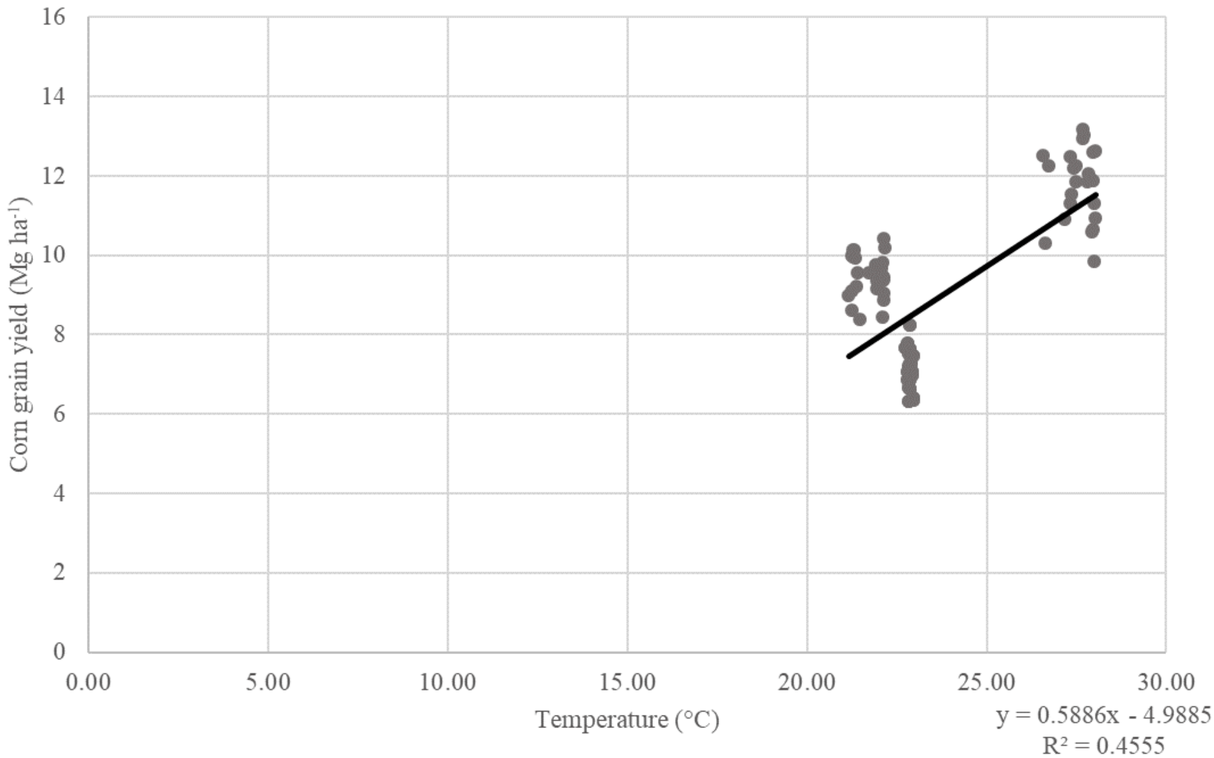


Figure 7.17. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 3/5 August (Springport 2018; Hickory Corners 2018); *p*-value = <0001.

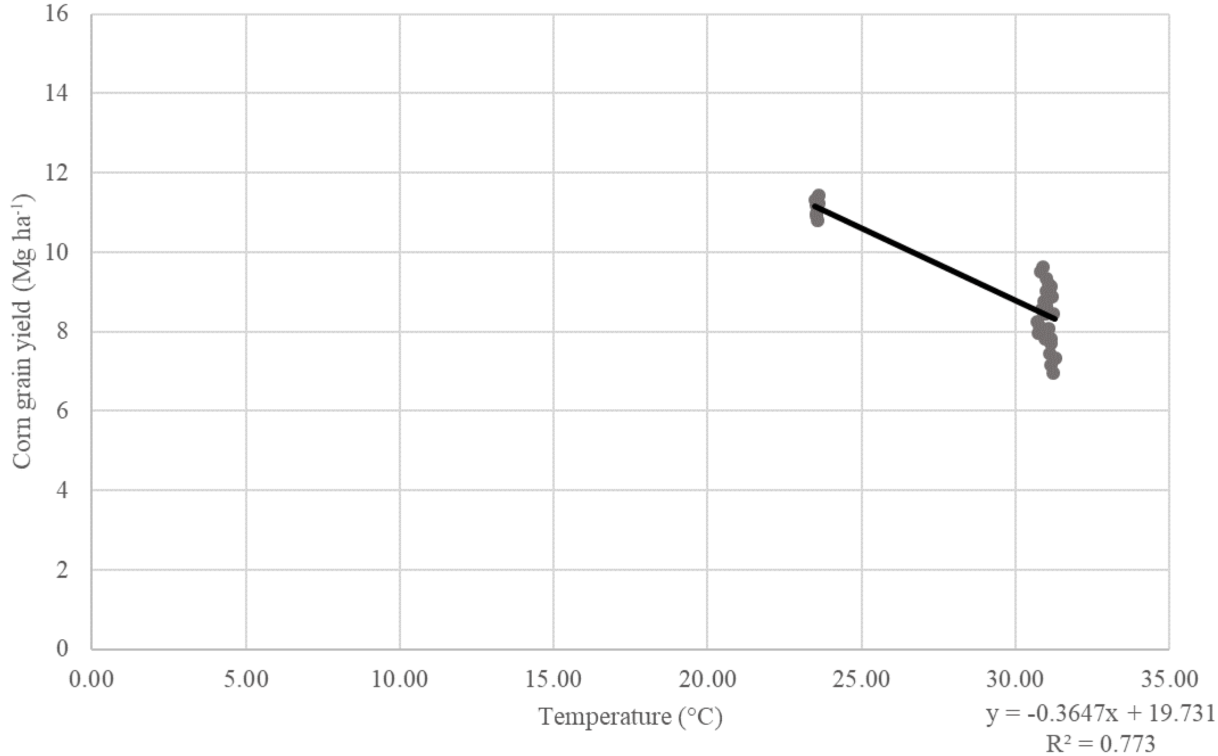


Figure 7.18. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 22 August (Springport 2018; Hickory Corners 2018); *p*-value = <0001.

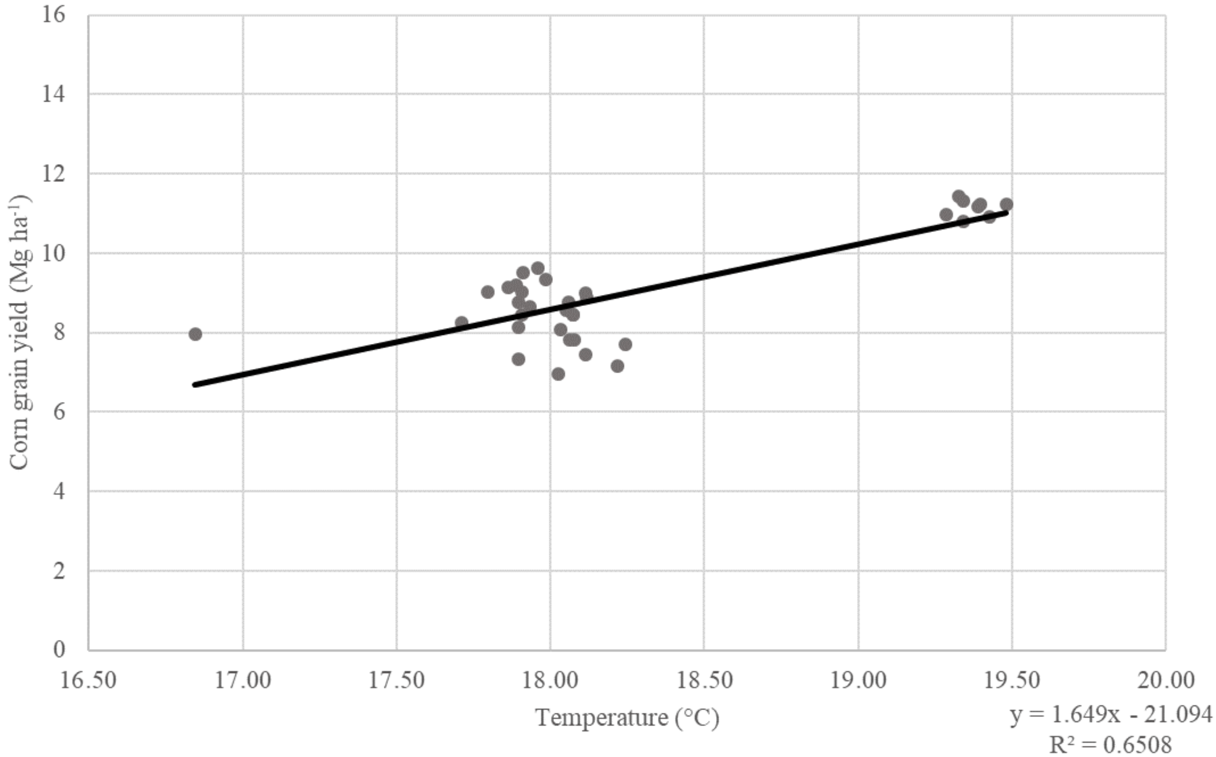


Figure 7.19. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 4 October (Springport 2018; Hickory Corners 2018); *p*-value = <0001.

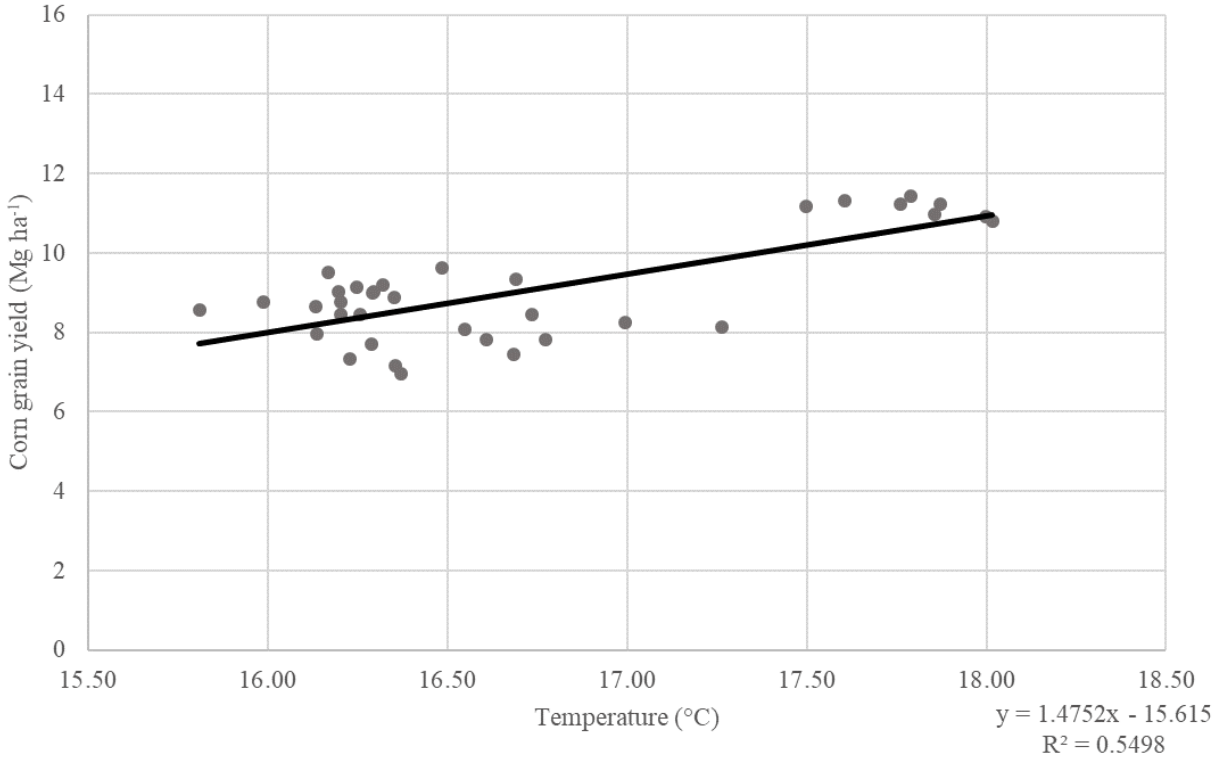


Figure 7.20. Correlation between corn grain yield and remotely sensed canopy temperature combined over locations where flyovers occurred on 16 October (Springport 2018; Hickory Corners 2018); *p*-value = <0001.

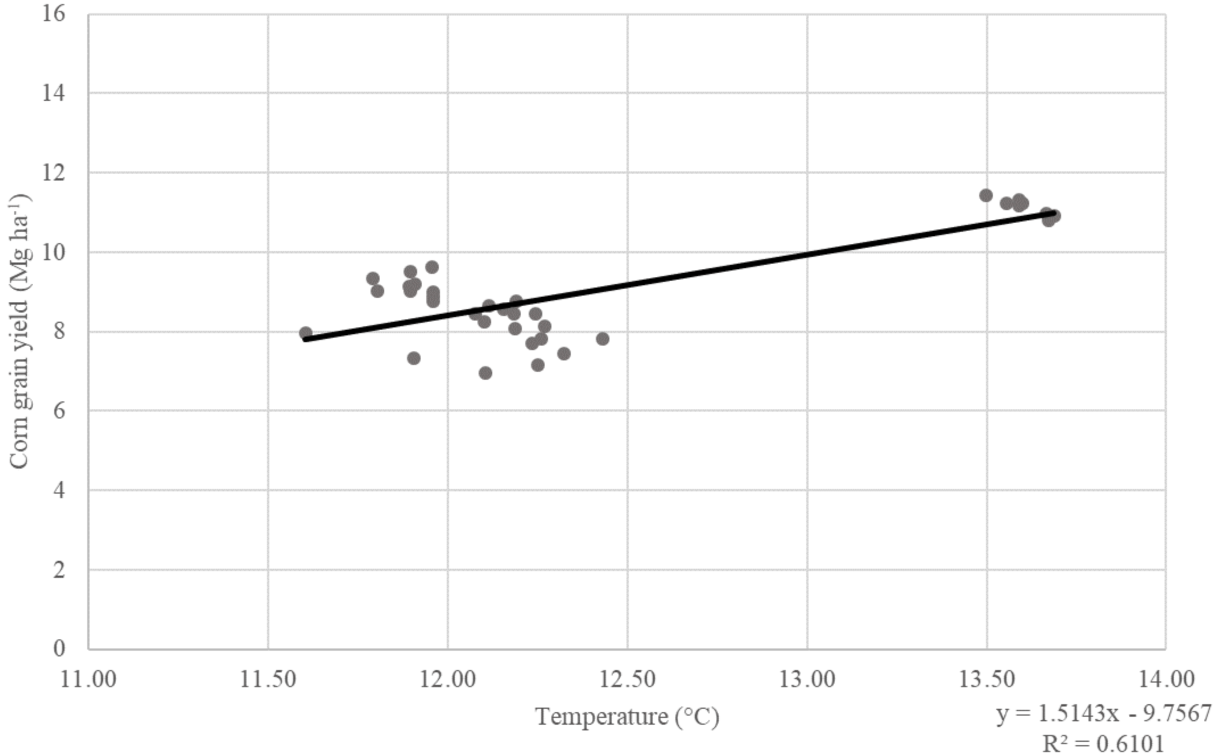
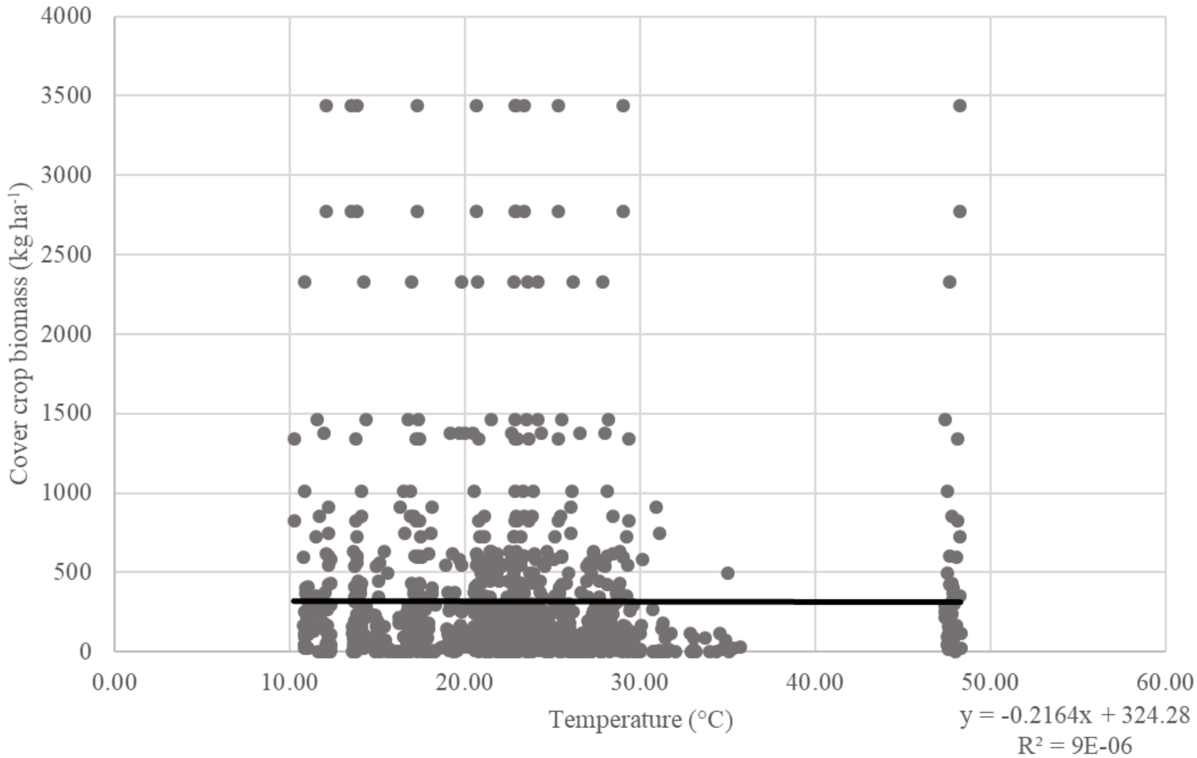


Figure 7.21. Correlation between cover crop biomass and remotely sensed canopy temperature combined over all site years; *p*-value = 0.8394.



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