IMPACT OF COVER CROP STRATEGIES ON PRODUCTIVITY OF CORN

Minnesota Corn Research & Promotion Council

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EXECUTIVE SUMMARY

Minnesota's cropland is among the most intensively cultivated in the world. Our dominant crops are corn and soybean in rotation, a synonymous of the Midwest U.S. agricultural landscape (Bigelow & Borchers, 2017). Their importance in our economy is undeniable; both crops are responsible for more than 80% of the $9.25 billion value of the state's field and miscellaneous crops in 2014 (USDA-NASS, 2020a). Corn and soybean are mostly grown using conventional practices, including high external inputs, a strategy that has been very successful in producing record amounts of grain. This success, however, has come at the cost of ecosystem services, including loss of diversity, excess nutrients showing up in surface and subsurface water, and soil degradation. Cover crops are promoted as an affordable and environmentally sound practice for sustainable production. Intuitively though, cover crops will use water and nutrients and may influence weed, insect and pathogen populations; yet, the strategy is expected to result in a more efficient use of resources while maintaining or improving productivity and enhancing the quality of the environment

While the benefits of cover crops are undisputable, their adoption in corn-soybean rotation practices is still limited in the region. This is due to a variety of reasons, including species performance in time and space, management practices in our cool-wet environment, effects on productivity of primary crop, and economics, among others. Resources use (e.g. soil water and nutrients) by cover crops depend on several factors, and therefore is highly variable. As a result, the **benefits of cover crops are realized over time, mainly if from rainfed production systems in cool-wet climates**, like in Minnesota. For example, the increase of heavy rainfall events in the spring along with poorly drained heavy soils drive important farmers' decision-making like fall tillage, so that fields dry up sooner in the spring to ensure timely planting.

Although the importance of our climate as a limiting factor to cover crops adoption in the state, opportunities exist to overcome such reality. For example, interseeding as early as V4-V6 corn, and as late as R5-R6 corn and R7-R8 soybean to increase the opportunity growth window. Early-interseeded cover crops may compete with primary crops for resources (i.e., water, nutrients, and light) and may be detrimental to productivity. On the other hand, late-interseeded cover crops will not compete with primary crops for resources as they start growing when primary crops are senescing; therefore, will not be detrimental to productivity. Late-interseeded winterkilled cover crops may produce biomass in the fall comparable to late-interseeded overwintering cover crops, and both strategies have the potential to reduce nitrogen (N) leaching and soil erosion. Late-interseeded winterkilled cover crops can facilitate timely planting of primary crops with reduced herbicide and tillage cost in the spring as compared to early- or late-interseeded overwintering cover crops. Yet, the performance of winterkill cover crops in the corn-soybean rotation in Minnesota is not well known.

These constraints to cover crops adoption established the framework of our research project. Our goal was to assess the **impact of cover crop strategies on the productivity of corn grown under different environments and production practices**. We hypothesized that: i) a combination of tillage and cover crop will improve cover crop performance without negatively effecting the productivity of the primary crops, and ii) regardless of the location, yield of primary crops will not be diminished with the use of cover crops. Objectives to test our hypothesis were:

1. Assess the viability of cover crop strategies on corn-soybean rotation under different tillage practices. Studies under this objective included:
    a. *Potential of winterkilled cover crops late-interseeded into corn*
    b. *Effect of tillage and winterkilled cover crops on N dynamics in corn-soybean rotations*

2. Determine the effect of cover crop strategies on growth and yield of corn and soybean produced across multiple environments. Studies under this objective included:
    a. *Effect of winterkilled and winter hardy cover crops on productivity of corn across MN*
    b. *Effect of cover crops on N dynamics in corn production across MN*
    c. *Water use of crops and cover crops*
    d. *Effect of early-interseeded cover crops on insect pest, predator, and parasitoid populations*

3. Determine the economic viability of cover crop strategies in corn production. This included:
    a. *Late-interseeded, winterkilled cover crops and tillage practices*
    b. *Early- and late-interseeded cover crops at multiple locations*

Cover crop studies in corn production systems were conducted on the University of Minnesota (UMN): i) Long-term Tillage Trial (LTTT) and ii) Long-Term Agricultural Research Network (LTARN) platforms. LTTT nodes are located at the UMN South West Research and Outreach Center (SWROC) near Lamberton and Southern Research and Outreach Center (SROC) at Waseca. LTARN nodes are located at the UMN North Central Research and outreach Center (NCROC) at Grand Rapids, SWROC, and SROC. The LTTT was initiated in 1990 to determine the impact of tillage practices on corn production systems; the no-till (NT), strip-till (ST), and conventional-till (CT) plots were used in this research project. The LTARN was initiated in 2013-2014 with the goal to provide a research platform for the development of novel and adaptive agricultural production strategies representing a range of soil types, and precipitation and temperature gradients; the corn-soybean plots were used in this research project.

Cover crops used in the trials were selected to reach multiple benefits; grasses to reduce N-leaching, legumes to improve soil fertility, and brassicas to alleviate soil compaction. Grass species were annual ryegrass [AR; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] and cereal rye (CR; *Secale cereale* L.), the legume species was crimson clover (CC; *Trifolium incarnatum* L.), and the brassica species was forage radish (FR; *Raphanus sativus* L.). These species are common cover crops in the region, as either monocrops or mixtures; CR overwinters, and is the most studied cover crop species. Treatments studied consisted on grasses as monocrops or mixed with the other cover crops to make two sets of four treatments each: ***set 1*** = AR, ARCC, ARCCFR, and NC (no cover as control); ***set 2*** = CR, CRCC, CRCCFR, and NC. The ***set 1*** was used in the LTTT studies (objective 1) and both sets were used in the LTARN studies (objective 2). Relevant results from our field studies follow:

Objective 1: Assess the viability of cover crop strategies on corn-soybean rotation under different tillage practices

a. *Potential of winterkilled cover crops late-interseeded into corn*

- Conventional tillage within corn produced the highest cover crop biomass as compared to the other tillage practices, possibly due to better seed-to-soil contact.
- Yield of primary crops was affected by weather and year. Tillage practice and cover crops had no effect on yield of corn and soybean.
- Cover crops can establish successfully in the fall, especially within corn. However, establishment and growth of cover crops was influenced by weather, tillage practices, and primary crop, rather than cover crops.
- Annual ryegrass established better and often outperformed CC and FR in mixtures. The 3-way mixture of ARCCFR tended to have more ground cover than the 2-way mixes and AR monoculture.
- Although these strategies can produce biomass within corn, it is unclear if the amounts produced can provide ecosystem services.
- The marginal performance of late-interseeded cover crops in soybean suggests that this strategy may not add value within that crop

b. *Effect of tillage on the performance of winterkilled cover crops and N dynamics in corn-soybean rotations*

- Nitrogen in grain and stover was not affected by tillage practice or cover crops, but varied significantly by location, year, and location x year interactions, evidencing that environment had more effect on N than tillage practice or cover crop strategy.
- Biomass-N of cover crops varied highly from year to year. Nitrogen in the 3-way mix of ARCCFR was consistently higher than the 2-way mix of ARCC and AR monoculture throughout the study.
- The C:N ratio was consistently higher in the ARCC as compared to ARCCFR and AR.
- Variations in soil residual N (NO_3-N) were primarily driven by year, location, and their interactions. More soil NO_3-N was observed in the fall and the next spring before planting than at the time of

seeding cover crops late in the season, which could have resulted from mineralization of primary crops residue.
- The monthly averages of NO_3-N concentration in the leachate did not reveal any consistent patterns among cover crop strategies within tillage practice in either primary crop.

Objective 2: Determine the effect of cover crop strategies on growth and yield of corn and soybean produced across multiple environments

a. *Effect of winterkilled and winter hardy cover crops on productivity of corn across MN*

- Early- and late-interseeded AR-based cover crop strategies produced greater total canopy cover and biomass by fall frost than CR-based strategies. These findings suggest that AR may be an equally good or better cover crop option compared with CR.
- Increased heat units due to early planting of late-interseeded cover crops did not translate into greater cover crop establishment or more growth. Conversely, early-interseeded cover crops naturally accumulated more GDD thereby producing greater canopy cover and biomass than late-interseeded cover crops in most cases.
- Our results show that interseeding cover crops into corn at V4-V6 corn produced highly variable results but was not detrimental to corn production. Regrowth of CR did not reduce soil moisture at corn planting or subsequent biomass- and grain-yield

b. *Effect of cover crops on N dynamics in corn production across MN*

- While not consistent, our results show that cover crops have the potential to reduce N losses. We also found that soil type matters: cover crops had no effect on soil NO_3-N in a well-drained loam soil but were reduced NO_3-N relative to no cover on moderately well drained and somewhat poorly drained clay loam soils. Late-interseeded CR-based cover crops were effective in reducing NO_3-N in the soil solution at all 3-study locations.
- Cover crops biomass-N was highly variable among locations and strategies. At Grand Rapids, the northernmost location, early-interseeded cover crops had higher biomass-N than late-interseeded cover crops. Early-interseeded AR-based cover crops at Grand Rapids had more biomass-N than CR-based cover crops, and AR accumulated more than mixtures. At Lamberton and Waseca, early- and late-interseeded ARCCFR and CRCCFR showed more biomass-N than monocultures and 2-sprecies mixtures of cover crops.
- Early-interseeded cover crops did not affect corn biomass- and grain-N. Late-interseeded cover crops, however, were associated with differences in corn biomass- and grain-N.

c. *Water use of crops and cover crops*

- Cover crops seeded late in the growing season of primary crops affected neither soil moisture dynamics nor yield of primary crops.
- The water use and efficiency of corn and soybean were both markedly affected by year, location, and the year x location interaction, but were not affected by cover crops. The average water use efficiency of corn and soybean was 696 and 234 lb DM/inch of water, respectively.

- The water use and efficiency of cover crops was affected by year, locations, and the year x location interaction, but was not affected by the cover crop strategy. During both fall and spring, and across locations, soil evaporation represented over 70% of the evapotranspiration of cover crops. The WUE of cover crops ranged from 2.3 lb DM/inch to 357 lb DM/inch.
- While cover crops may affect soil moisture and the water use and yield of primary crops, results from this study demonstrated that late-interseeded cover crops in the cool-wet climate of Minnesota did not have such effect

d. Effect of early-interseeded cover crops on insect pest, predator, and parasitoid populations

- At all location-years, the abundance of pest, parasitoids, and predators was affected by sampling date but was not affected by cover crop strategy.
- Among locations, pests were more abundant at Lamberton, followed by Waseca and Grand Rapids. Parasitoids were more abundant at Lamberton and Waseca in 2017 and at Grand Rapids in 2018.
- Predators were more abundant at Grand Rapids in 2017 but similar at all three locations in 2018. Predators collected with the pitfall traps were more abundant in Waseca, followed by Lamberton and Grand Rapids.

Objective 3: Determine the economic viability of cover crop strategies in corn production

- None of the cover crop strategies used was economically viable. Our research suggested that early- and late-interseeded cover crops into corn could increase variable costs and reduce farm profits, at least in the short run.
- It is important to note that our economic analysis considered neither the possibility of N credit nor the potential environmental benefits (i.e., enhanced soil health, biodiversity, reduction of NO_3-N loss, among others) from cover crops use. Moreover, the strategies evaluated in this project are just some of several others that should be investigated

The project supported two M.S, students: Hannah Rusch and Rabin KC, both defended in 2019 and are now pursuing their Ph.D; the former at the University of Florida and the latter at Michigan State. Hannah published an article in a peer review journal, and Rabin is preparing the submission of two manuscripts.

From 2016 to 2019, our outreach activities reached around 2000 individuals through field days, talks, and extension articles in our *Minnesota Crop News* blog (https://blog-crop-news.extension.umn.edu/). Research results were also presented at the MN AgExpo in 2017 and 2019. We also presented our results during three years at the American Society of Agronomy and several other professional meetings in the state.

CHAPTER 1 – THE PROJECT: IMPACT OF COVER CROP STRATEGIES ON PRODUCTIVITY OF CORN

SYNOPSIS

Minnesota's cropland is among the most intensively cultivated in the world. Our dominant crops are corn and soybean in rotation; both responsible for more than 80% of the $9.25 billion value of the state's field and miscellaneous crops in 2014 (USDA-NASS, 2020a). Corn and soybean are mostly grown using conventional practices, including high external inputs. Such technology is under scrutiny due to issues with soil erosion and nutrient losses; e.g., nitrogen in the form of nitrate (NO_3), which ends up water resources. Cover crops are promoted as affordable and environmentally sound as sustainable cropping practices. Intuitively, cover crops will use water and nutrients and may influence weed, insect and pathogen populations; yet, the strategy is expected to result in a more efficient use of resources while maintaining or improving productivity and enhancing the quality of the environment. The goal of this proposal was to **assess the impact of cover crop strategies on the productivity of corn grown under different environments and production practices.** The project was conducted at the University of Minnesota Research and Outreach Centers located in the north central (Grand Rapids), southwest (Lamberton), and southern (Waseca) regions (Figure 1.2), representing a range of soil type, precipitation, and temperature gradients.

BENEFIT OF THE PROJECT TO MINNESOTA CORN FARMERS

Cover crops use is increasing in Minnesota corn production systems. Information on basic agronomic practices, including species options, establishment, and most importantly, their effect on yield of corn is needed. This project addressed those issues by establishing a multi-practices, multi-location study, which allowed obtaining results scalable to a large number of corn producers. Issues addressed. including performance, water use, capacity to scavenge residual N, among others are related to the effect of cover crops on growth and yield of corn and soybean.

GOAL AND OBJECTIVES

The goal of this research project was to assess the impact of cover crop strategies on the productivity of corn grown under different environments and production practices. We hypothesized that: i) a combination of tillage and cover crop will improve cover crop performance without negatively effecting the productivity of the primary crops, and ii) regardless of the location, yield of primary crops will not be diminished with the use of cover crops. Specific objectives were:

4. Assess the viability of cover crop strategies on corn-soybean rotation under different tillage practices,
5. Determine the effect of cover crop strategies on growth and yield of corn and soybean produced across multiple environments, and
6. Determine the economic viability of cover crop strategies in corn production

This research directly addressed the 2016 MCR&PC corn production and stewardship priority category of **Production Stewardship Research/Development of conservation strategies such as cover crops for Minnesota corn production**. The use of multi-location field research allowed for a robust **assessment of the effect of several cover crop strategies on corn production.** We expect our results will help advance our understanding of those effects on soil water and N availability and the productivity of corn. This information is critical to corn growers' competitiveness while increasing sustainability efforts.

METHODS AND TIMELINES

LOCATIONS

Field experiments were conducted on University of Minnesota Research and Outreach Center facilities located within plant hardiness zones 3b (-30F to -35F) (Grand Rapids) and 4b (-25F to -20F) (Lamberton and Waseca) (https://planthardiness.ars.usda.gov). Trials under objective 1, hereafter referred to as ***cover crops and tillage practices,*** were located at Lamberton and Waseca. Trials under objective 2, hereafter referred to as ***cover crops at multiple locations,*** were conducted at all three locations.

Table 1.1 Soil physical and chemical characteristics at the three experimental locations in Minnesota, U.S.

Location	**Soil Layer (inches)**	**Particle-size distribution (%)**			**NO_3**	**OM**	**PH**
		Clay	*Silt*	*Sand*	*ppm*	*%*	
Grand Rapid	0-8	6.6	42.2	51.3	3.5	2.3	6.9
	8-16	7.2	40.2	52.6	4.8	1.1	6.4
	16-24	8.8	13.5	77.7	3.8	0.9	6.2
Lamberton	0-8	31.1	31.5	37.4	3.8	4.0	6.0
	8-16	34.1	31.6	34.3	2.9	3.2	6.6
	16-24	31.3	30.0	38.7	1.6	2.1	7.5
Waseca	0-8	31.7	38.6	29.8	2.5	4.8	6.4
	8-16	32.5	34.6	32.9	2.9	3.4	6.7
	16-24	33.9	34.1	32.0	2.2	2.2	7.0

Source: National Cooperative Soil Survey (NCSS)-USDA, 2020.

Overall, soils at Grand Rapids, Lamberton, and Waseca are characterized as well-drained, moderately well-drained, and poorly drained, respectively; soil organic matter (OM) is lower at Grand Rapids and higher at Lamberton and Waseca (Table 1.1).

The long-term average (LTA; 1990 – 2015) annual cumulative precipitation is 27.6 inches at Grand Rapids, 27.9 inches at Lamberton, and 36.3 inches at Waseca. For the same period, the average annual maximum/minimum air temperatures are 47F/30F at Grand Rapids, 56F/34F at Lamberton and 55F/35F at Waseca. Grand Rapids is cooler and drier than the other two locations; Waseca is the warmer and wetter location (Figure 1.1). The long-term air temperature and rainfall data were obtained from the Climate Data Online platform, of the National Oceanic and Atmospheric Administration (www.ncdc.noaa.gov/cdo-web/)

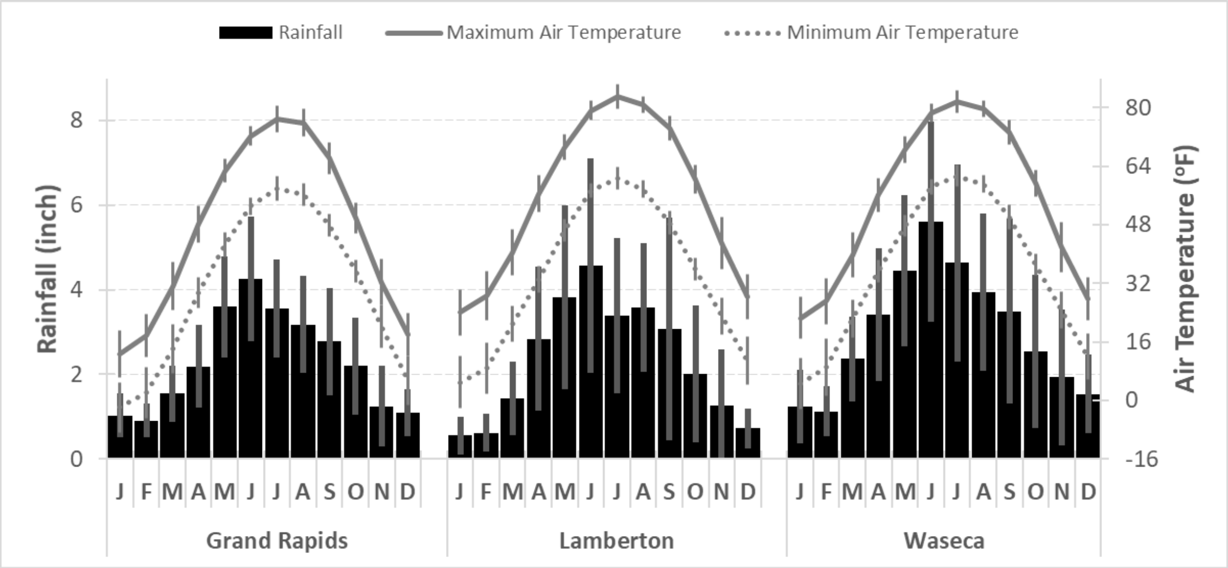


Figure 1.1 Long-term average (1990 – 2015) weather conditions at the experimental sites. Vertical lines denote ± 1 standard deviation.

THE EXPERIMENTS

Cover crops used in the trials were selected to reach multiple benefits; grasses to reduce N-leaching, legumes to improve soil fertility, and brassicas to alleviate soil compaction. Grass species were annual ryegrass [AR; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] and cereal rye (CR; *Secale cereale* L.), the legume species was crimson clover (CC; *Trifolium incarnatum* L.), and the brassica species was forage radish (FR; *Raphanus sativus* L.). These species are common cover crops in the region, as either monocrops or mixtures; CR overwinters, and is the most studied cover crop species. Treatments studied consisted on grasses as monocrops or mixed with the other cover crops to make two sets of four treatments each: ***set 1*** = AR, ARCC, ARCCFR, and

NC (no cover as control); ***set 2*** = CR, CRCC, CRCCFR, and NC. The ***set 1*** was used in the LTTT studies (objective 1) and both sets were used in the LTARN studies (objective 2).

COVER CROPS AND TILLAGE PRACTICES

Studies were conducted within a long-term tillage trial (LTTT) platform located at the SWROC near Lamberton (44°24’N, -95°31’W) and SROC in Waseca (44°06’N, -93°53’W), Minnesota. The dominant soils were characterized as moderately well-drained Normania loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) and well-drained Amiret loam (fine-loamy, mixed, superactive, mesic Calcic Hapludolls) at Lamberton and a poorly-drained Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) at Waseca (National Cooperative Soil Survey (NCSS)-USDA, 2020) at Waseca.

COVER CROPS AT MULTIPLE LOCATIONS

Studies within this objective were conducted on the University of Minnesota LTARN platform located at the NCROC in Grand Rapids (47°18’N, -93°53’W), SWROC near Lamberton, and SROC in Waseca (Figure 1.2). The dominant soils were characterized as well-drained Nashwauk loam (fine-loamy, mixed, superactive, frigid Oxyaquic Glossudalfs) at Grand Rapids, moderately well drained Normania clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) at Lamberton, and somewhat poorly drained Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls) (USDA-NRCS, 2020) at Waseca.

Figure 1.2 Location of the University of Minnesota NCROC (Grand Rapids), SWROC (Lamberton), and SROC (Waseca).

EXPERIMENTAL DESIGN

COVER CROPS AND TILLAGE PRACTICES

Trials within this objective were a) *potential of winterkilled cover crops late-interseeded in corn* and soybean and b) *effect of tillage and winter killed cover crops on N dynamics in corn-soybean rotations*. Trial [a] was designed as split-split plot with four replications in each site-year. Main plot was primary crop (corn and soybean), sub-plot was tillage practice (conventional-till, CT; strip-till, ST; and no-till, NT), and sub-sub-plot was cover crop strategy (AR, ARCC, ARCCFR, and NC). Sub-sub-plots were randomized within the sub-plots. Each experimental unit was 15 ft wide (six 30-in rows) and 54 ft long in Waseca, and 12 ft (five 30-in rows) wide and 66 ft long in Lamberton. Trial [b] included an additional study to determine the N mineralization potential of cover crop residues; details of the procedure are found in Chapter 3\N Mineralization from Cover Crop Residues.

COVER CROPS AT MULTIPLE LOCATIONS

Trials consisted on early- and late-interseeded cover crops into corn and late-interseeded into soybean at multiple locations. Early-interseeded cover crops were seeded at V4-V6 corn. Late-interseeded cover crops were seeded at R5-R6 corn and R7-R8 soybean. All trials were set as RCBD within the primary crop with four replications, except for the late-interseeded in corn trial at Grand Rapids, which had three replications. Corn plot size for the early-interseeded trial was 10 ft wide by 30 ft long at Grand Rapids and Lamberton and 15 ft wide by 30 ft long at Waseca. Plot size for the late-interseeded trials in both corn and soybean was 10 ft wide by 20 ft long at all locations. Cover crop treatments included two grass species (AR and CR) in monoculture and in 2- and 3-species mixtures. The 2-species mixtures included a grass + CC and are denoted as ARCC and CRCC. The 3-species mixtures included a grass + CC + FR and are denoted as ARCCFR and CRCCFR. A NC control was assigned to each grass species and are denoted as ARNC and CRNC. Only CR overwintered to resume grow in the spring and required termination; AR, CC, and FR winterkilled thereby eliminating the need for spring management. Thus, findings related to spring termination refer only to CR.

AGRONOMIC MANAGEMENT

In all trials, commonly used full-season corn and soybean were planted in 30-inch rows; both primary crops were harvested for grain. Fertilizer amounts were set for highly productive corn following the University of Minnesota guidelines (Kaiser et al., 2020). The NC plots were treated with glyphosate to control weeds. Plots rotated each year between corn and soybean. Cover crop seeds were weighed separately for each species and then mixed at seeding. Seeds were hand-broadcast as an attempt to mimic air seeding and to avoid seeds landing in the canopy. Seeding rates vary by cover crop strategy (Table 1.2).

Table 1.2 Cover crop seeding rates (lb/ac) used in the study

Cover crop	**Monoculture**		**2-species mix**		**3-species mix**	
	AR	*CR*	*ARCC*	*CRCC*	*ARCCFR*	*CRCCFR*
Annual Ryegrass (AR)	25		12.5		12.5	
Cereal Rye (CR)		60		30		30
Crimson Clover (CC)			20	20	15	15
Forage Radish (FR)					9	9

COVER CROPS AND TILLAGE PRACTICES

Major activities across locations were the same, but timing varied (Table 1.3) as a function of weather conditions. Strip-till was performed 15 d before planting corn and soybean to a depth of six inches and in 8-in wide strips using an 8-row strip-tiller with 30-in row spacing at both locations. At SWROC, CT was performed a day before planting in corn and soybean plots to a depth of 6 inches using a chisel plow. At SROC, however, CT was performed a day before planting soybean using a disc ripper and a field cultivator. Corn plots were field cultivated to the depth of 4 inches. Tillage and fertilization were performed only in the spring.

Table 1.3 Calendar of activities from 2016 to 2019 in trials within specific objective 1 at each study-site

Activity	**Lamberton**				**Waseca**			
	2016	*2017*	*2018*	*2019*	*2016*	*2017*	*2018*	*2019*
Corn/soybean planting	5/10	5/11	5/31	6/1 6/4	5/5	5/5		
Cover crop seeding	9/14 9/19	8/30 9/07	8/22	-	9/14 9/19	8/30 9/07	8/16	-
Corn/soybean harvest	10/05	10/23 10/26	10/31 10/18	10/25	9/28	11/1 10/23		10/25
Cover crop sampling	11/22	10/31	10/26	-		10/31		-

At Lamberton, glyphosate was applied once (0.75 lb a.e./ac) along with Fusilade (Fluazifop-P-butyl) (0.10 lb a.e./ac) at planting. At Waseca, glyphosate [N-(phosphonomethyl)glycine] was applied before planting (1.00 lb a.e./ac) and at V3-V4 leaf-collar stages of corn (0.75 lb a.e./ac). Corn DKC49-72RIB (99-d RM RR2) was planted in both locations at the rate of 36,000 seeds/ac. Soybean AG2035 was planted in both locations at the rate of 150,000 seeds/ac; in 2019, the soybean AG20X9 was used at SWROC. Both crops were planted at a depth of 2 inches in 30-in wide rows using a four-row John Deere 1700 MaxEmerge series planter at both locations.

At Lamberton, 178 lb N/ac in the form of urea [NH_2-CO-NH_2] were applied at planting along with 15 lb S/ac in the form of gypsum [$CaSO_4$ $2H_2O$]. At Waseca, a total of 145 lb N/ac in the form of urea along with 15 lb S/ac in the form of gypsum were applied; 56 lb N/ac at planting and the remaining at V6 corn. At both sites Agrotain® [N-(n-butyl) thiophosphoric triamide, NBPT], a urease inhibitor, was applied each time urea was used.

In 2017, cover crops were hand broadcasted at R5-R6 corn stages and R7-R8 soybean stage (early-Sep) at both locations. In 2018, cover crops were hand-broadcasted 15 d earlier; at the R3-R4 stage corn and R6 stage soybean (mid-Aug) to increase growing degree-days and opportunity for cover crop growth. Cover crops were lightly raked only in 2017 at SROC to increase seed to soil contact due to dry soil conditions.

COVER CROPS AT MULTIPLE LOCATIONS

Major activities across locations were the same, but timing varied (Table 1.4) as a function of weather conditions. All plots were strip-tilled 1-15 d before planting corn. Corn was planted into tilled strips at 35,000 seeds/ac at 2-in depth in 30-in wide rows. In both early- and late-interseeded trials, spring CR regrowth was terminated using 0.75 lb a.e./ac of glyphosate applied 1-7 d before planting. Corn in the early-interseed trial was a 76 RM hybrid (Pioneer P762AM1) at Grand Rapids, a 107 RM hybrid (Pioneer P0157AMX) at Lamberton, and a 99 RM hybrid (DEKALB DKC49-72RIB) at Waseca.

Table 1.4 Calendar of activities from 2016 to 2019 in trials within specific objective 2 at each study-site

Activity	**Grand Rapids**				**Lamberton**				**Waseca**			
	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Early-interseeded at multiple corn locations												
Cover crop sampling	-	5/15	5/22	-	-	4/28	5/7	-	-	4/21	5/14	-
Cover crop termination	-	5/22	5/22	-	-	5/4	5/8	-	-	4/23	5/7	-
Corn planting	5/10	5/22	5/22	-	5/19	5/12	5/19	-	5/5	5/5	5/17	-
Cover crop seeding	6/27	6/26	8/10	-	6/29	6/15	6/15	-	6/14	6/14	6/14	-
Corn harvest	11/9	10/13	10/13	-	10/16	10/24	10/8	-	10/29	10/29	9/29	-
Cover crop sampling	11/26	11/5	11/5	-	10/29	10/26	10/26	-	10/30	10/30	10/16	-
Late-interseeded at multiple corn and soybean locations												
Cover crop sampling	-	5/7	5/22	-	-	4/21	5/16	-	-	4/21	5/7	-
Cover crop termination	-	5/10	5/22	-	-	4/29	5/16	-	-	4/23	5/7	-
Corn planting	5/15	5/10	5/22	-	4/30	5/8	5/16	-	4/29	4/24	5/10	-
Cover crop seeding	9/20	9/3	8/10	-	9/14	8/31	8/14	-	9/14	9/4	8/13	-
Corn harvest	10/25	10/26	10/13	-	10/17	10/25	10/16	-	10/16	10/30	10/16	-
Cover crop sampling	11/9	11/9	11/5	-	11/14	10/30	10/20	-	11/15	11/1	10/27	-

Corn in the late-interseeded trial was a 76 RM hybrid (Pioneer P7632AM) at Grand Rapids and a 103 RM hybrid (DEKALB DKC53-56RIB) at Lamberton and Waseca. Soybean in LIM-CS were A00932 in 2016 and AG00937 in 2017 and 2018 at Grand Rapids; AG2031 in 2016, A2035 in 2017 and 2018, and AG20X7 in 2019 at Lamberton and Waseca.

Nitrogen fertilizer in the early-interseeded trial in corn was broadcast applied at 65 lb N/ac as urea within one week of corn planting with an additional 62 lb N/ac as urea sidedressed at V4-V6 corn. In the late-interseeded trial in corn at Grand Rapids and Waseca, 56 lb N/ac as urea and 15 lb S/ac as gypsum within one week of corn planting, and an additional 90 lb N/ac as urea was sidedressed at V4-V6 corn. In Lamberton, a single application of 120 lb N/ac as urea were sidedressed at V4-V6 corn due to wet field conditions.

The weed control strategy consisted on a post-emergence herbicide six weeks after corn planting; glyphosate and glufosinate {(RS)-2-Amino-4-(hydroxy(methyl)phosphonoyl)butanoic acid} were used in early- and late-interseeded cover crop trials, respectively.

Data Collection

In all experiments

In all trials, data collected included soil samples at different depths at the beginning and end of each growing season for nutrients content, concentration of N in the form of nitrate (NO_3-N) at a depth of 40 inches, and soil moisture content (Figure 1.3). Most common plant data collection across trials included ground cover, growth and development, canopy height, maximum leaf area index, grain and biomass yields, and tissue-N.

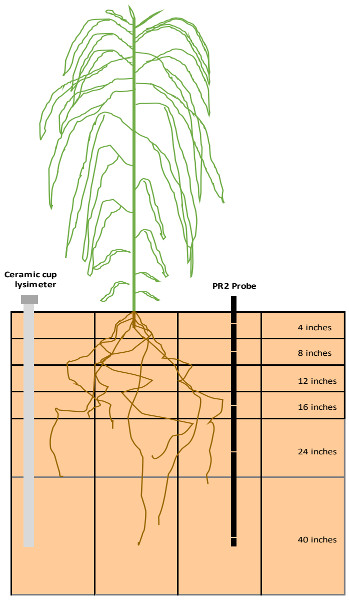


Figure 1.3 Soil moisture and N-nitrate monitoring set up

Soil – Baseline information was obtained at each location on samples taken at different depths at the beginning of the growing season. Nitrate-N measurements in the soil solution were conducted. Soil N, P, organic matter, cation exchange capacity, and sulphur were determined at six and 12 inches at the beginning and the end of each growing season. Residual soil NO_3-N and volumetric soil water content were measured in all experiments. Ceramic cups were installed at a soil depth of 40 inches to measure the concentration of NO_3-N in the soil solution throughout the growing seasons; samples were kept at 38F and analyzed for nitrate and ammonia within 1-4 weeks. Soil analysis was conducted in the spring before planting primary crops, in the summer before seeding cover crops, and in the fall before frost at both locations. Physicochemical analysis, including extractable NO_3- N, pH, OM, Bray P, CEC, K^+, Ca^{+2}, and Mg^{+3} were conducted at the Minnesota Valley Testing Laboratory (www.mvtl.com), New Ulm, MN.

The concentration of NO_3-N in the soil solution was obtained by collecting samples with ceramic suction cups of 0.1 MPa air-entry pressure (Soilmoisture Equipment Corp., Goleta, CA, USA). Ceramic suction cups were installed at 40-in depth in the harvest row of one plot per treatment only. A hand pump was used to create a 50 KPa vacuum 3-5 d before sample collection. Soil solution was sampled weekly; a total of 38, 48, and 42 samples were collected in 2017, 2018, and 2019, respectively. Soil solution was collected in 50-mL centrifuge tubes and frozen until laboratory analysis. The concentration of NO_3-N in the soil solution was determined by Vanadium (III) reduction via the manual spectrophotometric procedure (Doane and Horwáth, 2003).

Weather – Weather conditions during the experimental years were monitored using automated weather stations located at each location. Data collected included daily averages of maximum and minimum air temperature, solar radiation, and rainfall. Data from nearby NOAA stations (www.ncdc.noaa.gov/cdo-web/) and NASA POWER (https://power.larc.nasa.gov/) were used to fill gaps, primarily at Grand Rapids.

Crops – Plant count, plant sampling for growth and leaf area index, and phenological observations were conducted at regular intervals throughout the growing season on corn, soybean, and cover crops at each plot across all locations. Leaf area index (m^2 m^{-2}) was obtained through photosynthetically active radiation (PAR) readings taken with an LP-80 AccuPAR Ceptometer (www.metergroup.com; Pullman, WA). Readings were taken between 1000 and 1400 h in 10- to 15-d intervals. The Ceptometer was placed perpendicularly in the middle of the two center rows (www.metergroup.com; Pullman, WA), where three readings were taken and averaged. An external sensor attached to a 9-ft pole was used to measure above and below canopy PAR simultaneously. The below canopy PAR/above canopy PAR ratio known as *Tau*, was then calculated as an attempt to capture PAR efficiency between treatments.

Cover crop canopy cover was measured in the fall around the first frost day and before termination in the spring. Images were captured using a digital camera, and later uploaded into the mobile application Canopeo v 1.1.7 (Patrignani & Ochsner, 2015) to estimate fractional green canopy cover within a a 1-sqft quadrat. Simultaneously, all above ground biomass within the quadrat excluding weed biomass, if any, was collected. The biomass of each species was separated in cover crop mixes. The biomass was later dried in a forced-air oven at 140F until constant mass and then weighed.

Corn, soybean, and cover crop biomass were collected at the end of each growing season to determine productivity, tissue-N, and C:N ratios. Above ground biomass was measured 4-5 times during the growing seasons in cover crops, corn, and soybean. Samples were cut into small pieces using a chipper and collected in cloth bags to facilitate uniform drying. Plant samples were dried in a forced-air oven at 140F until constant mass and then weighed. Corn grain samples at R6 were used to separate grain from ears using a sheller, and soybean samples at R7-R8 were used to separate grain from the stover. Harvest Index was calculated as the ratio of economic yield to biological yield (Donald & Hamblin, 1976). Grain and plant biomass samples were later ground separately using Thomas Wiley Mill Model 4 with a 2-mm screen (www.thomassci.com), and subsamples taken in whirl-Pak bags to determine C and N with a vario MACRO cube (www.elementar.com/us.html). Grain yield, and biomass residue were obtained for corn and soybeans at the end of the growing season. Grain weight and moisture content of both crops were obtained at harvest using a two-row Kincaid 8-XP plot combine equipped with the weight and moisture-measuring device HarvestMaster GrainGage (www.junipersys.com).

Growing-degree days (GDD) were calculated at each growing season from planting to physiological maturity for corn and soybean, from seeding to two consecutive frost days for winterkilled cover crops (AR), and from seeding to spring-termination for overwintering cover crops (CR). Growing-degree days was calculated based on McMaster & Wilhelm (1997) using $GDD = \sum\left(\frac{T_{max}+T_{min}}{2} - T_{base}\right)$

Equation 1. Cardinal temperatures were based on McMaster & Wilhelm (1997) and Akyuz et al. (2017) for corn and soybean, respectively, Moot et al. (2000) for AR, and Nuttonson (1957) for CR.

$$GDD = \sum\left(\frac{T_{max}+T_{min}}{2} - T_{base}\right) \qquad \text{Equation 1}$$

where, T_{max} = maximum daily temperature and T_{min} = minimum daily temperature. To eliminate the effect of air temperature below or above the absolute minimum and maximum temperatures, the following constraints were used:

If $T_{max} > T_x \; then \; T_{max} = T_x$

If $T_{max} < T_{base} \; then \; T_{max} = T_{base}$

If $T_{min} < T_{base} \; then \; T_{min} = T_{base}$

COVER CROPS AND TILLAGE PRACTICES

Following corn and soybean emergence, soil volumetric water content and temperature were measured on 7- to 10-d intervals at each plot. A portable POGO Hydra Probe system equipped with Stevens HydraProbe II soil sensor (Stevens Water Monitoring Systems, Inc., Portland, OR) of 1.1-in diameter and sensing length of 2.25-in and the mobile application HydraMon, were used to monitor soil moisture and temperature. Data were recorded for 2018 and 2019 season from planting until corn and soybean reached the V6 and V3 stages, respectively. Readings were taken from three spots within a plot (on the crop row, and two spots between the rows- each at 7.5-in from the row).

Total above ground biomass was measured at the V6, VT/R1, and R6 stages of corn and V5/V6, R1, and R7/R8 stages of soybean. All plants within 3.3-ft row length in 2017 and 2018 and within 1.65-ft row length in 2019 were hand-harvested from the second row of each plot. Samples were then cut into small pieces using a chipper and collected in cloth bags to facilitate uniform drying. The samples were dried in a forced-air oven at 140F until constant mass and then weighed. Corn grain samples at R6 were used to separate grain from ears using a sheller, and soybean samples at R7-R8 were used to separate grain from the stover. Harvest Index was calculated as the ratio of economic yield to biological yield (Donald & Hamblin, 1976). Grain and plant biomass samples were later ground separately using Thomas Wiley Mill Model 4 with a 2-mm screen (www.thomassci.com), and subsamples taken in whirl-Pak bags to determine CHNS with a vario MACRO cube (www.elementar.com/us.html).

Grain weight and moisture content of both crops were obtained at harvest using a two-row Kincaid 8-XP plot combine equipped with the weight and moisture-measuring device HarvestMaster GrainGage (www.junipersys.com).

COVER CROPS AT MULTIPLE LOCATIONS

Soil moisture was collected on 7- to 10-d intervals in all CR-based strategies in LIM-CS. A factory-calibrated PR2 soil moisture probe with an HH2 handheld readout device (www.delta-t.co.uk) was inserted into an access tube installed in the center of each plot (Figure 1.3) to measure soil moisture as a percentage of volume. Three measurements per depth were taken in each plot, and the average was used as a single value. Results from soil moisture in the top 12 in were used in this study to represent an arbitrary maximum cover crop root length.

Three corn plants per plot were collected at physiological maturity. Corn was cut at 5 cm above the soil surface and ears were separated from stover to determine harvest index. Stover was chipped in the field using a chipper. Corn stover and ears were dried in a forced-air oven at 140F until constant mass and weighed. Corn grain weight and moisture content was measured after

Corn physiological maturity by harvesting the center two rows of each plot using a small-plot combine. Grain yield was calculated at 15.5 % moisture.

STATISTICAL ANALYSES

COVER CROPS AND TILLAGE PRACTICES

Data were analyzed using R (version 3.6.2; R Core Team, 2019). Grain yield, cover crop biomass, PAR, and cover crop canopy cover were analyzed separately using linear mixed effects model ANOVA to determine significant main effects and interactive effects using '*lmerTest*' (Kuznetsova et al., 2017). Analyses for each response variable were combined over time and space to address broad sense inference (Moore & Dixon, 2015). Location, year, tillage, cover crop strategies, and their interactions were considered fixed effects, and appropriate split-plot error terms were considered random effects. Visual representations were used to check the assumptions of normality and constant variance of the model residuals. If the combined analysis resulted in significant interactions, separate ANOVA was conducted on the response variables of interest. Tillage and cover crop strategies were considered fixed effects and split-plot error terms were considered random effects. Model residuals were used to diagnose for normality and the need for data transformation. Post hoc comparisons of all estimated marginal means were made on the response variables using a conservative Bonferroni's adjusted p values using the '*emmeans'* package (Lenth et al., 2019). Compact letter displays for significant differences were obtained using the *'multcomp'* package (Hothorn et al., 2008).

COVER CROPS AT MULTIPLE LOCATIONS

Data were analyzed at $P < 0.05$ by analysis of variance with a linear mixed effects model using the lmer package (Bates et al., 2015) in the R statistical software environment (R Core Team, 2013). Location, year, and cover crop strategy were considered fixed effects, and replication was considered a random effect. For analysis of soil moisture, depth was considered a fixed effect. Early-interseeded cover crop canopy cover and biomass at spring termination were analyzed separately by year due to no CR regrowth at Grand Rapids or Lamberton in 2019. When fixed effects were significant, means were compared with Tukey's honestly significant difference test at $P < 0.05$ using the *lsmeans* package in R (Lenth, 2016).

ECONOMIC ANALYSIS

The economic analysis was performed using a combination of data from objective 1 and objective 2 studies and ancillary data from the USDA-ERS Commodity Costs and Returns and Fertilizer Use and Price (USDA-ERS, 2020) and the University of Minnesota (Lazarus, 2020). The economic analysis was performed for each treatment according to the inputs used and field operations. Fertilizer prices were based on the 2020 prices from the United States Department of Agriculture Economic Research Service (USDA-ERS, 2020). Herbicide costs corresponded to the average of

2016 and 2017 for the Northern Great Plains (USDA-ERS, 2020). Cover crop, corn, and soybean seed prices were based on actual costs. Machinery cost was based on Lazarus (2020). The cost of fuel, lubricants, repair and maintenance, labor, power, implement depreciation and overhead (interest, insurance and housing) were included in machinery costs. We used the cost of no-till drill (\$60.88 ha_{-1}) and combine grain head (\$66.44 ha_{-1}) (Lazarus, 2020). Instead of the cost of hand planting and harvesting of oilseed crops. Corn and soybean grain prices corresponded to the average of 2016-2019 annual prices in Minnesota (\$0.12 kg^{-1}) (USDA-NASS, 2020c). The costs for land, crop insurance, storage, and drying were not considered because these were the same across treatments.

CHAPTER 2 – COVER CROPS AND TILLAGE PRACTICES: POTENTIAL OF WINTERKILLED COVER CROPS LATE-INTERSEEDED IN CORN AND SOYBEAN

ABSTRACT

The successful integration of cover crops in the conventional corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation in the U.S. upper Midwest is challenging due to poor establishment, use of fall tillage, and a short seeding season. Most research conducted in the region has assessed the benefits of winter hardy cover crops, but research on winterkilled cover crops seeded late in the growing season is very limited. Grower's interest in cover crops that winterkill lies in practical and economic reasons: to save time and reduce costs associated with herbicide and labor at termination. The objectives of this study were to 1) assess the establishment and growth of winterkilled cover crops interseeded late into corn and soybean grown within different tillage practices, and 2) determine the effect of those cover crops in the productivity of corn and soybean. The study was conducted in Lamberton and Waseca, Minnesota. Cover crops were hand-broadcast at R5-R6 corn and R7-R8 soybean in fall 2017 and at R3-R4 corn and R5-R6 soybean in fall 2018. Tillage practices were conventional, strip, and no-till; and cover crop strategies included annual ryegrass [AR; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] monoculture, AR = crimson clover (CC; *Trifolium incarnatum* L.), and AR + CC +forage radish (FR; *Raphanus sativus* L.). Results showed that growth of cover crops was marginal. The three-way mixture of ARCCFR produced the highest biomass (151 lb/ac), followed by AR (137 lb/ac) and ARCC at (122 lb/ac) when pooled across years, location, and primary crops. AR monoculture produced more biomass within corn in 2017 in both locations, suggesting that species richness does not always result in higher productivity. In mixtures, AR consistently produced more biomass than CC and FR; CC had the lowest germination and establishment. Cover crop biomass pooled across location, year, tillage, and cover crop strategy yielded 227 lb/ac in corn and 66 lb/ac in soybean. Cover crop canopy cover averaged 24 percent in corn and 8 percent in soybean during the whole study. The yield of primary crops was affected by weather and year, rather than the cover crop strategy and tillage practice. The practicality of winterkilled/late-interseeded cover crops lies in its potential to produce biomass and provide ground cover. Although these strategies can produce biomass within corn, it is unclear if the amounts can provide ecosystem services. Their marginal performance in soybean suggests that this strategy may not add value within that crop.

Keywords: annual ryegrass, crimson clover, forage radish, cover crop mixtures, maize, tillage practices

INTRODUCTION

The corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation dominates the U.S. Midwest region (Russell et al., 2009), the largest producer of corn and soybean in the country (USDA-NASS, 2020b). Corn is highly responsive to nitrogen (N), and growers apply it in rates higher than recommended to maximize yield (Sela et al., 2016; Vetsch et al., 2019). Consequently, the U.S. Midwest watersheds deliver the highest loads of N and P via leaching, contributing to the formation of the hypoxic zone in the Gulf of Mexico (Alexander et al., 2008). Other consequences include deteriorated soil health, polluted groundwater, reduced biodiversity, impaired agroecosystem functions, and increased dis-services (Foley et al., 2011; Hanrahan et al., 2018; Kladivko et al., 2014; Tiemann et al., 2015; Tilman, 1999). Because corn and soybean are likely to continue to be produced in the Midwest, the development of improved farming practices is a necessity for the sustainability of the system.

Cover crop benefits have been realized since long ago (Odland & Knoblauch, 1938). Cover crops reduce N losses via leaching (De Bruin et al., 2005; Meisinger & Ricigliano, 2017; Strock et al., 2004), improve soil quality and health (Lal, 2016), increase species diversity (Drinkwater & Snapp, 2007), increase functional diversity (Elhakeem et al., 2019), and suppress weeds (Mirsky et al., 2011). However, in the U.S. upper Midwest the adoption of the practice is challenging due to weather conditions (Rusch et al., 2020), leading to poor field establishment (Noland et al., 2018; Rusch et al., 2020; S. S. Snapp et al., 2005). Moreover, most cover crop studies in the region involve cereal rye (*Secale cereale* L.), a cold-tolerant species that withstands our winter conditions (Rusch et al., 2020; S. S. Snapp et al., 2005; Wilson et al., 2013) that produces high biomass and uptake residual soil nitrate (Feyereisen et al., 2006; Strock et al., 2004). Cereal rye, however, is also reported to reduce corn yield due to allelopathic effects when herbicide-terminated at corn planting (Johnson et al., 1998). Besides, CR has the potential to attract pests such as true armyworm (*Mythimna unipuncta* Haworth) and cutworms (*Agrotis ipsilon* Hufnagel), which can potentially injure corn (Dunbar et al., 2016). Cover crop strategies that do not need spring termination, yet produce enough biomass in the fall and can provide agroecological benefits are options to CR.

In the past 50 years, the number of days with heavy rainfall has tripled in the Midwest U.S., particularly in the spring (J. L. Hatfield et al., 2013). This change, when coupled with poorly drained heavy soils, can result in wet conditions in the spring (Randall & Vetsch, 2005). Therefore, farmers tend to practice fall tillage after harvest so that the field dries up sooner in the spring to ensure timely planting. These factors evidence the significant challenge in adopting cover crops and conservation tillage practices in the region, particularly in southern Minnesota. Due to the limited window opportunity to get cover crops established, cover crops may be interseeded as early as V4-V6 corn, and as late as R5-R6 corn and R7-R8 soybean (Brooker et al., 2020; Rusch et al., 2020). Early-interseeded cover crops can compete with primary crops for resources such as water, nutrients, and light and can impact crop yields (Curran et al., 2018). Late-interseeded winterkilled cover crops can produce biomass in the fall comparable to late-interseeded overwintering cover crops with the potential to reduce N leaching and soil erosion in optimal weather conditions (Rusch et al., 2020). Besides, late-interseeded winterkilled cover crops can facilitate the timely planting of primary crops with reduced herbicide and tillage cost in the spring (Grimmer & Masiunas, 2004), as compared to overwintering cover crops (Grimmer & Masiunas, 2004; Johnson et al., 1998). However, little is known about the effect of winterkilled cover crops in crop productivity, their potential to provide agroecosystem services, and their performance in northern regions with a long history of tillage practices.

The goal of this study was to assess the effect of crops and tillage practices on the performance of winterkilled cover crops interseeded late in the corn and soybean growing season. Specific objectives were to 1) determine the combined effect of crop and tillage practice on the establishment and biomass production of winterkilled, late-interseeded cover crops, and 2) assess the effect of winterkilled late-interseeded cover crops on growth and yield of corn and soybean.

MATERIALS AND METHODS

Treatments in this study were as follows:

The study was conducted in Lamberton and Waseca, Minnesota. Cover crops were hand-broadcast at R5-R6 corn and R7-R8 soybean in fall 2017 and at R3-R4 corn and R5-R6 soybean in fall 2018. Tillage practices were conventional- (CT), strip- (ST), and no-till (NT); and cover crop strategies included annual ryegrass [AR; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] monoculture, AR + crimson clover (CC; *Trifolium incarnatum* L.), and AR + CC + forage radish (FR; *Raphanus sativus* L.).

A thorough description of the procedures for this trial is provided in Chapter 1, Methods and Timeline section. This include description of locations, experimental design, management, data collection (Figure 9.7), and statistical analysis procedure. Methods not described in Chapter 1 are detailed under this section.

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Overall, weather during the experimental years was highly variable (Figure 9.1). In 2017, growing season (May-Oct) monthly average air temperature was within 3.6F of the LTA (LTA) in both locations. Overall, 2018 was cool in both locations, notably April, which was 11F and 13F cooler than the LTA in Lamberton and Waseca, respectively. The monthly average air temperature in

2019 growing season was within 3.6F of the LTA in both locations. February was 13F cooler at Lamberton and 11F cooler at Waseca in 2019. Total rainfall during the 2017 growing season was higher than the LTA at Lamberton, and lower than the LTA at Waseca; the former received 24 inches and the latter received 26 inches rainfall. Rainfall in 2018 was higher than the LTA in both locations with 31.2 inches at Lamberton and 33.6 inches at Waseca (Table 2.1).

Table 2.1 Long-term average (LTA) of monthly rainfall totals and maximum (Tmax) and minimum (Tmin) air temperature at SWROC near Lamberton, MN and SROC, Waseca, MN. Experimental years 2016, 2017, 2018, and 2019 are shown as departures from the LTA.

Month	**LTA (1990-2015)**			**Deviation from Long-Term Average (LTA) Weather Conditions**											
				Rainfall (inches)				**Maximum Temperature (F)**				**Minimum Temperature (F)**			
	R (in)	Tmax (F)	Tmin (F)	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Lamberton															
Jan	0.6	24	5	-0.3	-0.1	-0.1	-0.1	0.2	1.1	0.1	-5.1	2.7	6.5	-0.6	-3.0
Feb	0.6	29	9	0.1	-0.6	0.0	1.2	2.2	12.8	-6.9	-14.4	7.5	12.0	-8.2	-12.6
Mar	1.4	40	21	0.5	-1.1	0.1	1.3	8.2	0.8	-6.0	-6.8	9.2	1.4	0.5	-5.1
Apr	2.8	57	33	0.7	1.6	-1.1	3.4	2.2	0.6	-13.4	-2.7	3.7	3.5	-9.0	1.6
May	3.8	69	46	1.5	0.7	0.7	0.7	2.5	-1.0	7.2	-5.2	0.3	0.1	6.9	-1.8
Jun	4.6	79	57	-2.0	-1.9	3.5	0.0	2.4	1.7	0.5	0.9	2.0	0.7	5.1	1.3
Jul	3.4	83	61	3.5	0.6	2.1	1.2	-0.9	0.8	-1.1	-1.4	1.9	0.7	1.3	2.8
Aug	3.6	81	58	1.7	1.3	0.1	-1.4	-0.3	-5.3	-0.8	-3.0	2.4	-1.5	2.8	-0.7
Sep	3.1	74	48	2.2	-0.9	3.5	3.0	-0.3	1.1	-1.7	0.8	4.6	3.6	4.3	5.4
Oct	2.0	60	36	0.8	3.9	0.8	1.9	1.1	-1.0	-6.9	-8.4	2.5	0.6	-3.8	-2.1
Nov	1.3	43	23	0.7	-1.2	-0.2	-0.1	7.9	0.0	-9.9	-6.0	8.3	-1.6	-5.9	-1.6
Dec	0.7	28	11	0.3	-0.3	1.2	0.7	-2.7	-1.3	0.7	-0.8	-2.9	-3.2	3.0	1.4
Year	**27.9**	**56**	**34**	**9.9**	**2.2**	**10.6**	**11.8**	**1.9**	**0.9**	**-3.0**	**-4.1**	**3.5**	**2.0**	**-0.1**	**-1.0**
Waseca															
Jan	1.2	23	5	-0.8	0.2	0.6	0.0	-0.2	3.0	-2.4	-2.8	2.6	8.6	-2.9	-0.7
Feb	1.1	27	9	-0.3	0.4	0.0	1.9	3.9	11.4	-5.2	-10.3	6.9	11.3	-8.9	-12.4
Mar	2.4	40	22	-0.2	-0.9	-1.2	-0.4	8.7	0.2	-3.3	-6.0	7.9	1.0	-0.7	-7.1
Apr	3.4	56	35	-1.4	-0.6	0.1	0.8	2.9	2.5	-13.6	-2.3	2.5	4.4	-11.5	-0.4
May	4.4	68	48	-0.7	0.7	0.8	1.9	2.3	-0.4	8.1	-5.9	0.0	-0.2	6.3	-3.0
Jun	5.6	78	58	-0.9	-1.5	0.2	-2.3	3.6	3.7	0.8	-0.7	0.8	-0.3	4.0	0.7
Jul	4.6	82	61	4.3	1.9	-0.3	1.8	0.5	2.7	-0.3	0.0	2.1	1.5	-0.4	2.3
Aug	3.9	80	59	3.8	0.0	0.8	1.4	2.3	-3.0	-0.2	-2.4	2.5	-3.1	0.0	-1.6
Sep	3.5	73	50	7.4	-1.5	7.0	3.2	3.7	2.4	0.6	1.2	6.0	2.1	4.1	5.0
Oct	2.5	59	37	0.6	1.6	0.6	3.4	5.2	0.2	-6.2	-5.9	4.3	2.6	-3.1	-2.4
Nov	1.9	42	25	-0.3	-1.8	-0.6	0.4	12.6	-1.4	-9.5	-7.1	9.0	-2.5	-8.1	-3.6
Dec	1.5	28	12	0.6	-0.6	0.6	0.0	-2.1	-1.2	1.4	1.8	-1.7	-4.7	4.7	0.5
Year	**36.3**	**55**	**35**	**12.1**	**-2.0**	**8.8**	**12.2**	**3.7**	**1.7**	**-2.3**	**-3.2**	**3.6**	**1.8**	**-1.2**	**-1.7**

Similarly, 2019 rainfall was 25.9 inches at Lamberton and 33.9 inches at Waseca. Rainfall event occurred within a week of seeding cover crop in both sites in 2017 and 2018, with Waseca receiving the highest rainfall in 2018 as compared to other site-years. In Lamberton, total weekly rainfall ranged from 0 to 0.60 inches after seeding cover crops in 2017 and 2018, respectively. At Waseca, however, the total weekly rainfall ranged from 0.20 to 1.6 inches in 2017 and 2018, respectively (Table 2.1).

GROWING DEGREE DAYS

Cumulative GDD (°C) from planting to maturity in 2017, 2018, and 2019, respectively, was 1562, 1550, and 1520 for corn and 1310, 1318, and 1278 for soybean at Lamberton and 1605, 1748, 1611 for corn and 1351, 1482, and 1348 for soybean at Waseca. Cumulative GDD from seeding to fall frost for cover crops at Lamberton and Waseca, respectively, was 474 and 570 in 2017 and 661 and 851 in 2018. The additional accumulation of ~200 GDD was due to around 15-d of earlier seeding in 2018 as compared to 2017 at both locations (Figure 2.1).

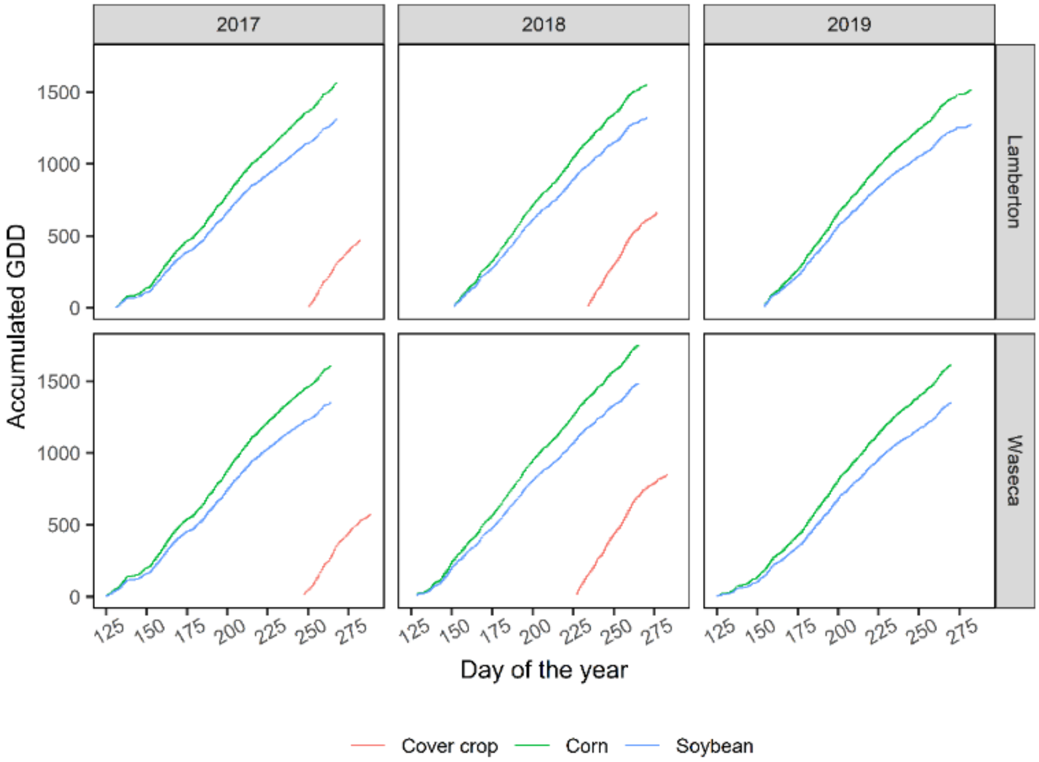


Figure 2.1 Accumulated growing-degree days (°C) for corn, soybean, and cover crops at Lamberton and Waseca, MN in 2017, 2018, and 2019.

EFFECT OF WINTERKILLED COVER CROPS IN CORN GRAIN YIELD

Corn grain yield was affected by year, tillage, year x location, year x tillage, and year x location x tillage interactions. Neither location nor cover crop strategies affected grain yield (Table 2.2).

Table 2.2 Significance of fixed effects on corn and soybean grain, cover crop (CC) biomass and ground cover, and tau (ratio of below- to above-PAR; PAR = Photosynthetically Active Radiation)

Source of variation	**Response variable**							
	Grain yield		**Cover crop biomass**		**Cover crop ground cover**		**Tau**	
	Corn	**Soybean**	**Corn**	**Soybean**	**Corn**	**Soybean**	**Corn**	**Soybean**
Y	0.000***	0.000***	0.960	0.000***	0.036*	0.000 ***	0.000***	0.000***
L	0.140	0.005**	0.002**	0.011*	0.001 **	0.004**	0.000***	0.004**
T	0.003**	0.239	0.032*	0.080.	0.103	0.034 *	0.310	0.157
C	0.697	0.763	0.050*	0.008**	0.000 ***	0.083.	0.982	0.892
Y x L	0.000***	0.007**	0.000***	0.017*	0.000 ***	0.15	0.527	0.000 ***
Y x T	0.000***	0.307	0.698	0.329	0.840	0.315	0.024*	0.817
L x T	0.694	0.000***	0.365	0.546	0.013 *	0.097.	0.039*	0.029 *
Y x C	0.437	0.939	0.024*	0.003**	0.034 *	0.013 *	0.996	0.968
L x C	0.831	0.599	0.715	0.290	0.172	0.304	0.956	0.996
T x C	0.265	0.729	0.997	0.924	0.639	0.892	0.994	0.999
Y x L x T	0.019*	0.017*	0.513	0.434	0.111	0.101	0.510	0.386
Y x L x C	0.504	0.836	0.902	0.380	0.678	0.227	0.981	0.998
Y x T x C	0.623	0.998	0.095.	0.977	0.156	0.972	0.870	0.999
L x T x C	0.448	0.606	0.317	0.944	0.275	0.931	0.746	0.987
Y x L x T x C	0.581	0.994	0.601	0.962	0.935	0.942	0.971	0.999

Significance of fixed effects (P > F) on response: corn and soybean yield, cover crop biomass and ground cover, and relative tau at Lamberton and Waseca, MN in 2017-2019. Numbers followed by ***, **, *, and a single dot are significant at 0.001, 0.01, 0.05, and 0.1 level.

In Lamberton, pooled average corn grain yield was 12044 lb/ac (13.5 Mg ha^{-1}) in 2017, which was higher than both 2018 (10350 lb/ac – 11.6 Mg ha^{-1} –) and 2019 (9127 lb/ac – 10.23 Mg ha^{-1} –). Corn yield at Lamberton was consistently higher in CT compared to ST and NT each year, but differences were not significant. Corn yield among cover crop strategies and tillage practices were not significantly different within each year. At Waseca corn grain yield was lower in 2018 (8297 lb/ac – 9.3 Mg ha^{-1} –) as compared to 2017 (10795 lb/ac – 12.1 Mg ha^{-1} –) and 2019 (13918 lb/ac – 15.6 Mg ha^{-1} –) (Figure 2.2). Yield differences among site-years could be due to the effect of weather rather than the effect of cover crop strategies. In fact, an event of hailstone during the grain-filling period in 2018 may have contributed to comparatively lower yields. As at Lamberton, corn yield at Waseca was not affected by tillage or cover crop strategy within each year.

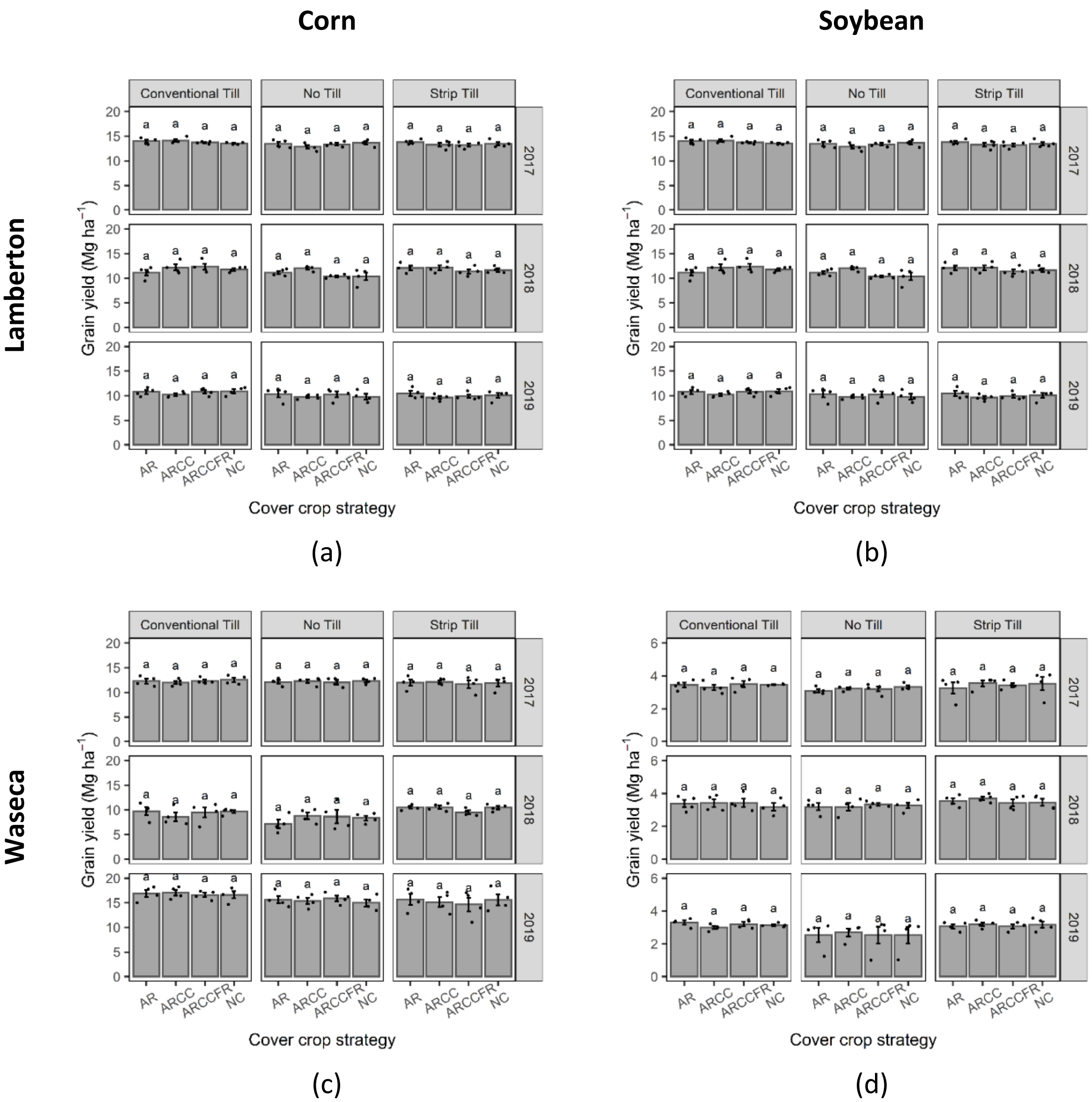


Figure 2.2 Grain yield of corn and soybean at SWROC near Lamberton and SROC, Waseca from 2017 to 2019. Bars followed by same letters are not significantly different at P ≤ 0.05 within each tillage practice each year. Error bars represent SEM (n=4), and dot represent data points. AR = annual ryegrass; ARCC = AR + crimson clover; ARCCFR = AR + CC + forage radish; NC denotes no cover (control).

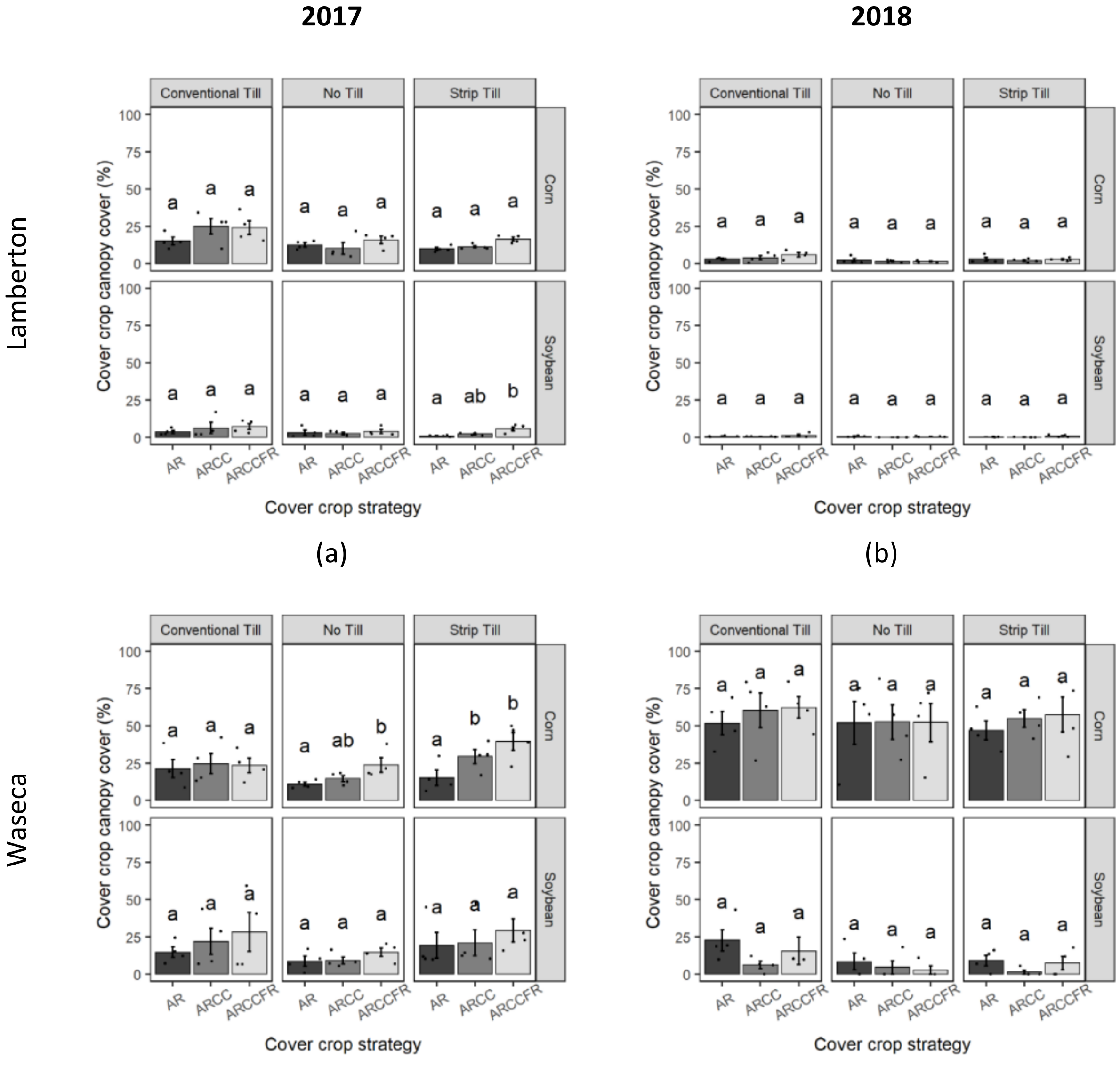
EFFECT OF WINTERKILLED COVER CROPS IN SOYBEAN GRAIN YIELD

Soybean yield was affected by year, location, year x location, location x tillage, and year x location x tillage interactions; neither tillage nor cover crop strategies affected soybean yield (Table 2.2). At Lamberton, the pooled average yield over tillage and cover crop strategy was 3658 lb/ac (4.1 Mg ha^{-1}), which was similar to 2018 (359 lb/ac – 4.0 Mg ha^{-1} –); yield at 2766 lb/ac (3.1 Mg ha^{-1}) in 2019 was the lowest. At Waseca, the pooled average yield was significantly lower than at

Lamberton. Soybean grain yield at Waseca was 3031 lb/ac (3.4 Mg ha^{-1}) and 2855 lb/ac (3.2 Mg ha^{-1}) in 2017 and 2018, respectively, while in 2019 was 2587 lb/ac (2.9 Mg ha^{-1}) (Figure 2.2).

COVER CROP CANOPY COVER

Canopy cover of cover crops was affected by year, location, cover crop strategy, the year x location, location x tillage, and year x cover crop strategy interactions. Within soybean, canopy cover varied by year, location, tillage, and interaction of year and cover crop strategy (Table 2.2).



(a) (b)

(c) (d)

Figure 2.3 Cover crop canopy cover in fall at Lamberton and Waseca. Bars followed by same letters are not significantly different at P ≤ 0.05 within tillage practice and year. Bars represent SEM (n=4) and dot a data point. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish.

At Lamberton in 2017, within corn, cover crop canopy cover was not affected by strategy across tillage practices. Within soybean, the three-way mix strategy (ARCCFR) was significantly different from AR within ST. However, in 2018, canopy cover was not affected by cover crop strategy within any tillage practices for both corn and soybean. At Waseca in 2017, within corn plots, canopy cover was different between cover crop strategy within strip- and no-till. However, for soybean plots, canopy cover did not vary among cover crop strategy within any tillage practice. In 2018, differences in canopy cover were not observed between cover crop strategy within tillage practices for both corn and soybean (Figure 2.3).

COVER CROP BIOMASS

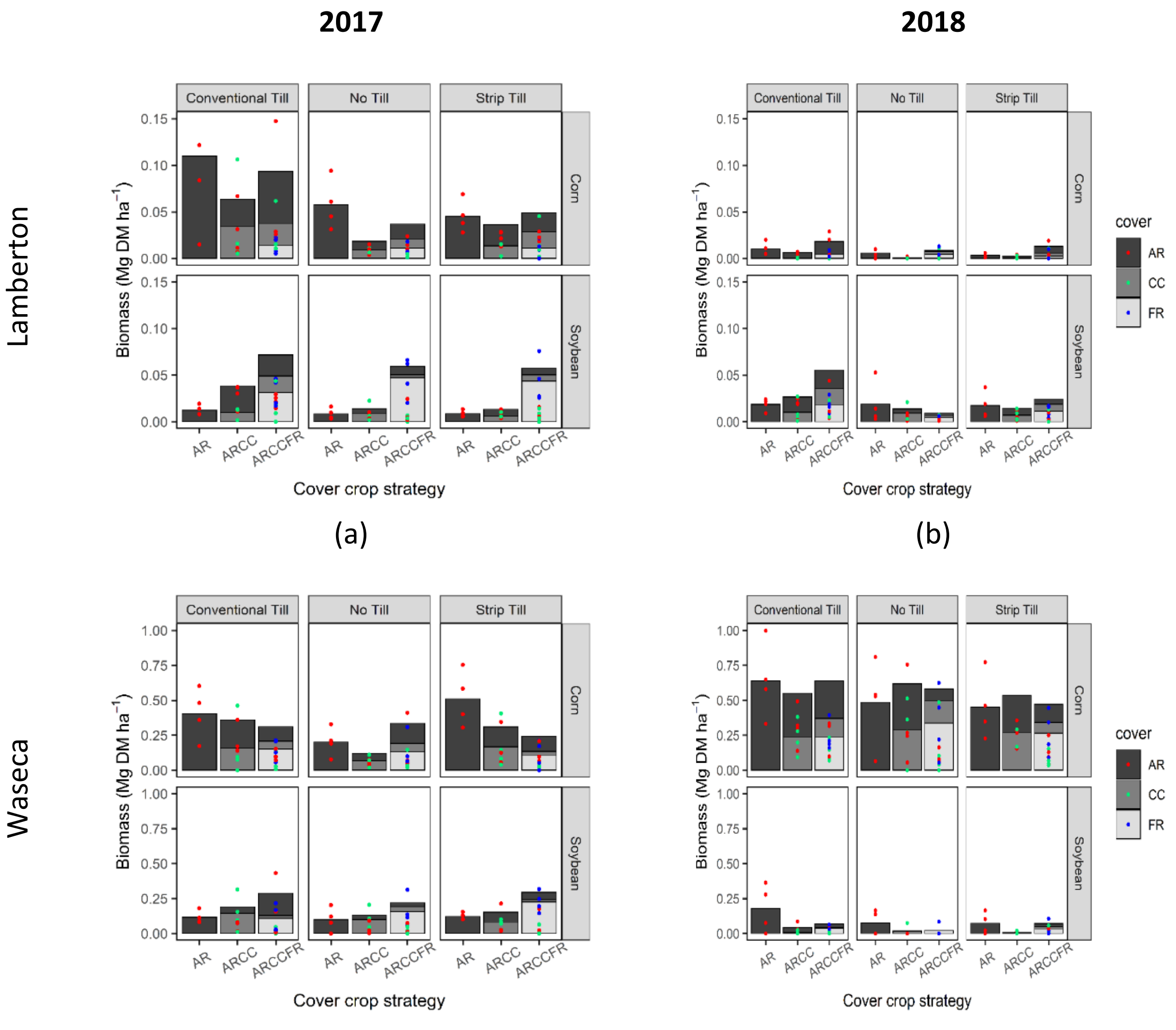
Cover crop biomass within corn was affected by location, tillage, cover crop strategy, and the year x location interaction. Within soybean, cover crop biomass was affected by year, location, cover crop strategy, and the year x cover crop strategy interaction (Table 2.2).

When pooled over corn, Lamberton site produced 51 lb DM/ac (0.057 Mg DM ha^{-1}) and 20 lb DM/ac (0.022 Mg DM ha^{-1}) cover crop biomass on average in 2017 and 2018, respectively. Within soybean plots, Lamberton produced only 27 lb DM/ac (0.031 Mg DM ha^{-1}) in 2017 and 6 lb DM/ac (0.007 Mg DM ha^{-1}) in 2018. Waseca, on the other hand, produced significantly higher biomass compared to Lamberton in both years, averaging 278 lb DM/ac (0.311 Mg DM ha^{-1}) in 2017 and 557 lb DM/ac (0.624 Mg DM ha^{-1}) in 2018 within corn plots. Pooled over soybean, Waseca produced 165 lb DM/ac (0.185 Mg DM ha^{-1}) and 55 lb DM/ac (0.062 Mg DM ha^{-1}) in 2017 and 2018, respectively.

Cover crops were seeded ~15-20 d earlier in 2018 in both locations. However, results show that early seeding did not always result in higher cover crop biomass production in Lamberton, which is consistent with experiment conducted in similar spatial and temporal environments (Rusch et al., 2020). More than cover crop strategy and tillage practices, variation in cover crop biomass was due to weather, namely light, rain, temperature, and hailstone events.

When pooled over tillage practices, average cover crop biomass significantly varied within corn plots, with CT producing higher biomass than ST and NT. This difference may be as a result of higher seed to soil contact in CT plots, which favors germination (Fisher et al., 2011). However, within soybean plots, no differences in cover crop biomass was observed among tillage practices.

Within cover crop strategy with 2-way and 3-way mixes, AR growth outperformed other species within a mix; biomass produced, however, mas marginal (Figure 2.4). Biomass production in cover crop strategy including mixes did not consistently produce higher biomass than cover crop monoculture in this experiment. This result is consistent with studies where mixtures did not produce more biomass than cover crop monocultures (Finney et al., 2016).



(a) (b)

(c) (d)

Figure 2.4 Cover crop dry biomass produced in fall at SWROC near Lamberton and SROC, Waseca. Different colors within a bar represent different species within a mix, and each dot represents data points. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish.

In this study, AR that did not emerge in the fall within the soybean plots, but emerged in the next spring within corn plots at planting, suggesting that winterkilled late-interseeded cover crops have weed potential in the next season if germination does not occur in the previous season. This experiment suggests that winterkilled late interseeded cover crops into corn can produce biomass comparable to early-interseeded cover crop in the fall. For example, fall cover crop biomass from this study was similar to the biomass produced by the same species interseeded early into corn (Rusch et al., 2020). However, biomass production within soybean seemed to be challenging and minimal to provide enough ground cover due to limited light as a result of dense foliage of the primary crop.

CONCLUSIONS

Yearly variations on establishment and growth of cover crops were explained by weather, tillage practices, and crop, rather than cover crop strategy. Annual ryegrass established better and often outperformed CC and FR in mixtures. Although the 3-way mixture of ARCCFR did not always result in higher biomass production, it had more ground cover than the 2-way mixes and AR monoculture. FR showed winter injury earlier than AR and CC, and CC consistently had slower germination and growth.

Conventional tillage within corn produced the highest cover crop biomass as compared to the other tillage practices, possibly due to better seed-to-soil contact. No differences in cover crop biomass were observed due to tillage practices in soybean. Results from this study suggest that summer annual cover crops can establish successfully in the fall, especially within corn. Cover crops interseeded late in the season had no effect on yield of corn and soybean.

Although the cover crops used in this study do not overwinter, seeding late in the season can produce biomass and provide ground cover in the fall after harvest in corn. However, there is limited information on the effect of cover crop biomass and ground cover on N cycling and soil organic matter.

CHAPTER 3 – COVER CROPS AND TILLAGE PRACTICES: EFFECTED OF TILLAGE AND WINTERKILLED COVER CROPS ON N DYNAMICS IN CORN-SOYBEAN ROTATIONS

ABSTRACT

Winterkilled cover crops are an attractive option to growers if they can provide ecosystem services similar to winter annual cover crops. The objective of this study was to advance our understanding of the fate of N as affected by late-interseeded winterkilled cover crops in corn and soybean rotation within different tillage practices. Specific objectives were to 1) assess the effect of cover crops in the soil, 2) estimate the N uptake of late-interseeded winterkilled cover crops, and its effect in corn and soybean, 3) assess the potential of cover crops to reduce residual soil NO_3-N, and 4) determine the effect of late interseeded winterkilled cover crops on net N mineralization. This study was nested within the study 1, where in situ N mineralization potential in the corn and soybean growing season was assessed. Cover crops and tillage practices significantly affected soil organic matter at 4 inches depth in spring after two seasons in Lamberton. Nitrogen in corn and soybean stover and grain was not affected by cover crops or tillage practices during the whole study. Over crop biomass-N varied by strategy within corn and soybean, and by strategy and tillage in soybean. Within corn, the 3-way mix of ARCCFR produced more N (8.25 lb/ac) than ARCC (6 lb/acre) and AR monoculture (6.5 lb/acc) when pooled over years and location. Within soybean, cover crop biomass-N was 3.5, 1.1, and 2.0 lb/ac in ARCCFR, ARCC, and AR, respectively. Pooled over years, cover crop biomass-N was significantly higher in Waseca (8 lb/acc) than in Lamberton (1 lb/ac). The 2-way mixture of ARCC strategy consistently had higher C:N than the AR monoculture and the 3-way mix of ARCCFR strategy, even though it produced lower biomass throughout the study. The pooled averages of C:N were 11:1, 12:1, and 10:1 for AR, ARCC, and ARCCFR, respectively. Cover crops did not affect the residual soil NO_3-N in the fall and spring, indicating that their N use was not significant. Residual soil NO_3-N was always higher in the fall and spring than at cover crop seeding. We did not see consistent pattern in NO_3-N in the soil solution during the study. Net N mineralization showed a decreasing trend as the season progressed, but was higher within corn as compared to soybean. Although cover crops used some residual N in the fall, biomass-N mineralized before it was available to next season corn because C:N was very low. Our results suggest that winterkilled cover crops interseeded late in the season do not have a marked effect on ecosystem services.

Keywords: nitrate nitrogen, cover crops, nitrogen use, residue mineralization

INTRODUCTION

Nitrogen (N) is one of the most essential nutrients to corn (*Zea mays* L.) growth (Sinclair & Horie, 1989). When more than needed is applied to maximize yield (Sela et al., 2016), part of the unused N is lost via leaching and runoff, causing environmental impairment and further contributing to its low N use efficiency (NUE), estimated to be only 32% (Raun et al., 2002).

Cover crops have been proven to provide ecological benefits, even in cold and harsh climates (Blanco-Canqui et al., 2015; Kladivko et al., 2014; S. S. Snapp et al., 2005; Strock et al., 2004). However, their adoption is not widespread, mainly due to weather conditions (Rusch et al., 2020), input costs (Roth et al., 2018), and wet soil conditions in the spring (Vetsch et al., 2019). The lack of knowledge on the synchrony of cover crop biomass-N release and corn N demand (Nevins et al., 2020) adds to these limitations. Cover crops uptake soil-N to produce biomass (Finney et al., 2016; Ruis et al., 2019; Thapa et al., 2018). Cereal rye (*Secale cereale* L.) for example, has shown to be consistent in biomass production and effective in uptaking residual NO_3-N, therefore reducing NO_3-N leaching to groundwater (SARE, 2007). However, less is known about the potential of winterkilled cover crops in providing agroecological benefits. Winterkilled cover crops may also be early- or late-interseeded in the primary crops growing season.

Nitrogen mineralization is the conversion of organic N into plant-available forms of ammonium (NH_4^+) and nitrate (NO_3^-); N immobilization is the opposite process (Hart et al., 1994). Cover crops affect the N cycle through mineralization and immobilization. Understanding the soil-N mineralization can help improving the prediction of N availability (Snapp and Borden, 2005) and subsequently fertilizer recommendations.

The goal of this study was to advance our understanding of the fate of N as affected by late-interseeded winterkilled cover crops in corn-soybean rotation practices within different tillage practices. Specific objectives were to 1) assess the effect cover crops in soil physico-chemical properties, 2) estimate the N uptake of cover crops and its effects in corn and soybean productivity, 3) assess the potential of cover crops to reduce residual soil NO_3-N, 4) determine the effect of cover crops on net N mineralization.

MATERIALS AND METHODS

Treatments in this study were as follows:

The study was conducted in Lamberton and Waseca, Minnesota. Cover crops were hand-broadcast at R5-R6 corn and R7-R8 soybean in fall 2017 and at R3-R4 corn and R5-R6 soybean in fall 2018. Tillage practices were conventional- (CT), strip- (ST), and no-till (NT); and cover crop strategies included annual ryegrass [AR; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot] monoculture, AR + crimson clover (CC; *Trifolium incarnatum* L.), and AR + CC + forage radish (FR; *Raphanus sativus* L.).

A thorough description of the procedures for this trial is provided in Chapter 1, Methods and Timeline section. This include description of locations, experimental design, management, data collection, and statistical analysis procedure. Methods corresponding to additional studies not described in Chapter 1, are detailed under this section.

N MINERALIZATION FROM COVER CROP RESIDUES

We conducted a study during the 2018 and 2019 growing seasons to determine the N mineralization potential from cover crop residues, a necessary supplement to our N dynamics study presented in this chapter. The study consisted on buried bags nested in all treatments of the main experiment in Chapter 2 and this chapter. The study was set as a classic split-plot in time with three replicates each site-year. Repeated measures were taken from the buried bags in a fixed interval of 15 d. The study was started before fertilizing the fields. Samples at seven points within a plot were taken in the top 6-in of soil with a regular soil auger (AMC Inc., ID) to make a composite sample. Polyethylene bags filled with 1 lb of the composite soil were buried equidistant at six inch depth in the harvest row of each plot. Wire stake flags were pinned to each bag to determine their location later in the season. Within no-tilled plots, polyethylene bags were placed over the soil surface to mimic no-tilled conditions. Bags were recovered in 15-d intervals.

Soil from removed bags was air-dried, ground, and 1g of soil sample weighed and placed into 15mL centrifuge tubes for analysis. Results were used to determine the net mineralization as described in **Error! Reference source not found.**:

$$Net\ Mineralization = \frac{\left[(NO_3^- + NH_4^+)_{d_{(i+n)}} - (NO_3^- + NH_4^+)_{d_i}\right]}{\Delta d} \qquad \text{Equation 2}$$

where,

d_i = total organic N on initial day, when bags were buried; $d_{(i+n)}$ = total organic N on day buried bags were removed, and Δd = number of days from d_i to bag removal at $d_{(i+n)}$. Results are expressed on a gravimetric basis (µg N g^{-1} dry soil d^{-1}).

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Weather conditions during the experimental years were as described under Chapter 2\Results and Discussion\Weather Conditions.

SOIL PROPERTIES

At Lamberton, after two years of cover cropping, soil organic matter was the only soil variable affected (Table 3.1). Within each tillage practice, more soil organic matter was observed consistently in the 3-way mix (ARCCFR) than the 2-way mix (ARCC) and the monoculture (AR). Pooled over tillage practice, CT had slightly higher organic matter (1.95 mg/lb – 4.3 mg kg $^{-1}$ –) than NT (1.93 mg/lb – 4.27 mg kg $^{-1}$ –) and ST (1.84 mg/lb – 4.05 mg kg $^{-1}$ –). This difference in organic matter in CT could be due to cooler and wetter conditions in ST and NT as compared to CT, which may result in decreased N-mineralization. At Waseca, no detectable effects of cover crops and tillage practices were observed in soil properties when measured in spring 2019 after two seasons of cover crops use (Table 3.2).

Table 3.1 Significance of fixed effects (P > F) on soil properties in the top 8-inch (20 cm) soil layer sampled in spring 2019 at SWROC near Lamberton, MN. Values in parentheses are one standard deviation. ANOVA is reported by tillage and cover crop treatment in a corn-soybean rotation after two growing seasons of cover cropping.

Tillage	**Cover crop strategy**	**pH**	**OM**	**Bray P**	**K^+**	**Ca^{+2}**	**Mg^{+3}**	**CEC**
					(mg kg $^{-1}$)			meq 100 g $^{-1}$
Conventional Till	AR	5.9 (0.6)	4.1 (0.35)	23 (13.8)	118 (8.6)	2294 (498)	475 (52)	20 (1)
	ARCC	5.8 (0.3)	4.4 (0.34)	19 (6.2)	116 (21.7)	2241 (430)	487 (60)	20 (2)
	ARCFR	5.7 (0.3)	4.0 (0.57)	21 (10.3)	140 (36.8)	2223 (397)	482 (61)	20 (1)
	NC	5.8 (0.6)	4.3 (0.33)	16 (6.8)	109 (12.1)	2189 (332)	457 (35)	20 (1)
No Till	AR	5.5 (0.2)	4.2 (0.39)	18 (6.2)	104 (12.4)	2063 (243)	436 (28)	21 (1)
	ARCC	5.5 (0.6)	4.3 (0.31)	22 (11.5)	112 (15.0)	2197 (369)	466 (60)	20 (1)
	ARCFR	5.5 (0.2)	4.3 (0.34)	20 (7.8)	110 (15.2)	2117 (217)	456 (31)	21 (1)
	NC	5.7 (0.4)	4.2 (0.29)	19 (7.3)	113 (12.6)	2299 (423)	476 (41)	21 (1)
Strip Till	AR	6.1 (0.7)	4.0 (0.28)	17 (6.5)	121 (9.7)	2350 (355)	460 (28)	19 (2)
	ARCC	5.9 (0.7)	3.9 (0.23)	18 (13.3)	116 (13.8)	2273 (443)	459 (48)	20 (1)
	ARCFR	5.7 (0.3)	4.1 (0.25)	14 (6.2)	110 (15.8)	2186 (384)	445 (43)	19 (1)
	NC	5.8 (0.3)	4.1 (0.33)	18 (7.4)	108 (15.6)	2242 (332)	463 (38)	19 (1)
Mean		5.75	4.2	19	115	2223	463	20
Tillage (T)		0.19	0.009**	0.37	0.13	0.72	0.22	0.003**
Cover crop strategy (C)		0.22	0.01*	0.75	0.17	0.66	0.55	0.91
T x C		0.26	0.2	0.47	0.004**	0.29	0.2	0.58

Numbers followed by ** and * are significant at 0.01 and 0.05 level. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR +CC + forage radish, and NC = no cover (control).

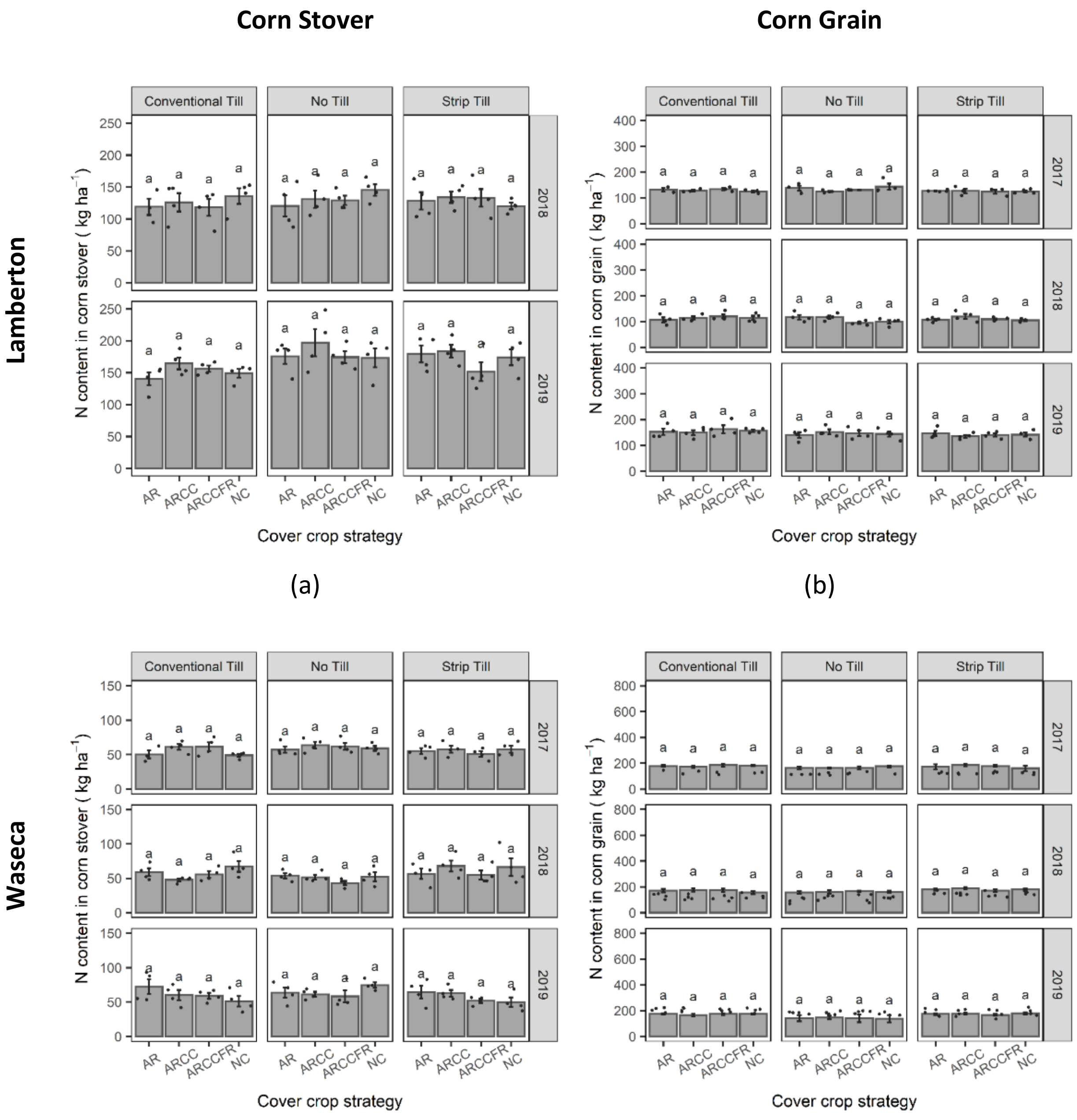
Table 3.2 Significance of fixed effects (P > F) on soil properties in the top 8-inch (20 cm) soil layer sampled in spring 2019 at SROC, Waseca, MN. Values in parentheses are one standard deviation. ANOVA is reported by tillage and cover crop treatment in a corn-soybean rotation after two growing seasons of cover cropping

Tillage	Cover crop strategy	pH	OM	Bray P	K^+	Ca^{+2}	Mg^{+3}	CEC
					(mg kg^{-1})			meq 100 g^{-1}
Conventional Till	AR	7.1 (0.6)	6.3 (0.8)	15 (4.7)	163 (27.0)	4622 (605)	475 (52)	20 (1)
	ARCC	7.1 (0.5)	6.3 (0.9)	23 (11.5)	169 (35.2)	4542 (498)	487 (60)	20 (2)
	ARCFR	6.9 (0.6)	6.2 (0.7)	21 (9.8)	156 (25.9)	4540 (721)	482 (61)	20 (1)
	NC	7.0 (0.6)	6.5 (0.8)	23 (7.5)	178 (52.8)	4387 (547)	457 (35)	20 (1)
No Till	AR	6.6 (0.1)	6.3 (0.6)	21 (17.0)	140 (20.3)	4599 (1116)	436 (28)	21 (1)
	ARCC	6.7 (0.8)	6.5 (0.5)	19 (9.2)	149 (11.7)	4298 (1025)	466 (60)	20 (1)
	ARCFR	6.5 (0.8)	6.3 (0.8)	19 (11.2)	158 (50.1)	4324 (934)	456 (31)	21 (1)
	NC	6.6 (1)	6.5 (0.6)	21 (12.0)	147 (27.2)	4275 (959)	476 (41)	21 (1)
Strip Till	AR	6.5 (0.7)	6.6 (0.5)	25 (15.9)	165 (43.0)	4245 (795)	460 (28)	19 (2)
	ARCC	6.7 (0.6)	6.3 (1)	18 (13.3)	146 (21.4)	4276 (928)	459 (48)	20 (1)
	ARCFR	6.9 (0.7)	6.7 (0.3)	20 (7.8)	156 (37.9)	4699 (986)	445 (43)	19 (1)
	NC	6.6 (0.8)	6.5 (0.6)	23 (15.6)	152 (27.7)	4409 (1019)	463 (38)	19 (1)
Mean		6.76	6.4	21	157	4435	471	28
Tillage (T)		0.42	0.69	0.93	0.16	0.91	0.99	0.08
Cover crop strategy (C)		0.72	0.77	0.82	0.96	0.41	0.82	0.1
T x C		0.33	0.44	0.43	0.43	0.26	0.63	0.65

AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish, and NC = no cover (control).

CORN BIOMASS- AND GRAIN-N

We observed that corn biomass-N was affected by the year x location interaction, but was not affected by cover crop strategy in both site years (Table 3.3). Results pooled over tillage and cover crop strategy showed the highest corn biomass-N at Lamberton: 132 lb/ac (148 kg ha^{-1}) in 2019, compared to 98 lb/ac (110 kg ha^{-1}) in 2018, and 116 lb/ac (130 kg ha^{-1}) in 2017. At Waseca, grain-N was significantly higher in 2019 (171 lb/ac – 192 kg ha^{-1} –) compared to 2018 (113 lb/ac – 127 kg ha^{-1} –), and 2017 (109 lb/ac – 122 kg ha^{-1} –). This difference in N accumulation is consistent with higher corn grain yield in 2019, which we report in Chapter 2. Corn grain-N pooled averages across years and cover crop strategies were near identical: AR = 116 lb/ac (130 kg ha^{-1}), ARCC = 116 lb/ac (130 kg ha^{-1}), ARCCFR = 115 lb/ac (129 kg ha^{-1}), and NC = 114 lb/ac (128 kg ha^{-1}) at Lamberton and AR = 136 lb/ac (152 kg ha^{-1}), ARCC = 133 lb/ac (149 kg ha^{-1}), ARCCFR = 132 lb/ac (148 kg ha^{-1}), and NC = 136 lb/ac (153 kg ha^{-1}) at Waseca (Figure 3.1). Such results suggest that cover crops had little to no effect on soil-N availability and the performance of corn.



(a) (b)

(c) (d)

Figure 3.1 Corn biomass- and grain-N at SWROC near Lamberton, MN and SROC, Waseca, MN from 2017 through 2019. Bars followed by the same letters are not significantly different at P ≤ 0.05 within each tillage practice each year. Error bars represent SEM (n=4), and dots represent data points. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish, and NC = no cover (control).

Our results support previous studies conducted in the region reporting that corn biomass-N is near identical among cover cropped treatments with some differences observed earlier in the season (Basche et al., 2016; S. Snapp & Surapur, 2018). In some studies, cover crops were seeded early in the growing season, and therefore produced higher biomass than what we found. In this study, cover crop and tillage had no effect in corn biomass-N, and we attribute these findings to low biomass production by the winterkilled cover crops.

Table 3.3 Significance of fixed effects on corn and soybean grain- and biomass-N, cover crop biomass-N, and cover crop C:N ratio

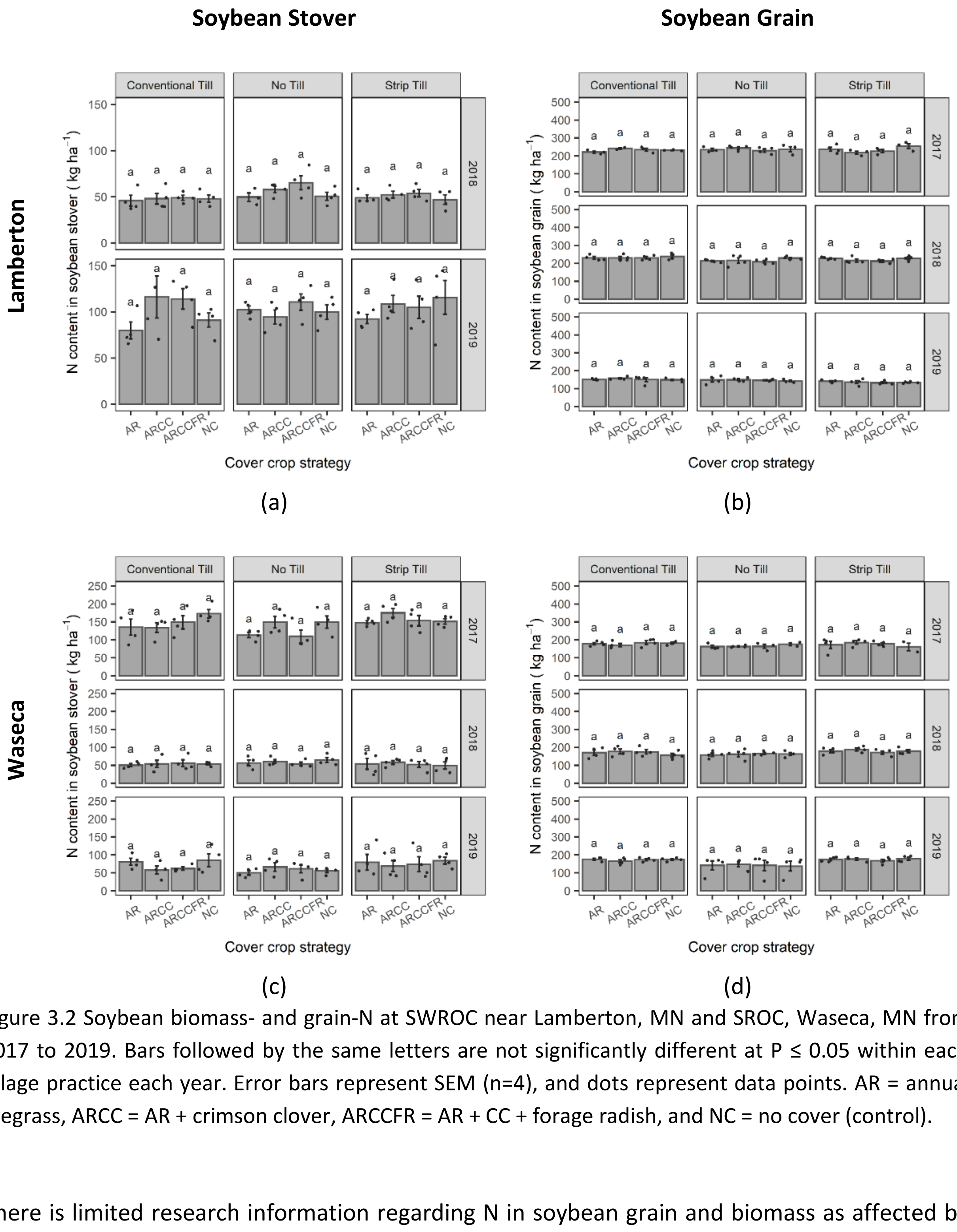
Source of variation	**Grain-N**		**Stover-N**		**Cover crop biomass-N**		**Cover crop C:N ratio**	
	Corn	*Soybean*	*Corn*	*Soybean*	*Corn*	*Soybean*	*Corn*	*Soybean*
Year (Y)	0.000***	0.000***	0.000***	0.000***	0.253	0.000***	0.755	0.011*
Location (L)	0.000***	0.000***	0.000***	0.065	0.003**	0.005**	0.013*	0.054
Tillage (T)	0.067**.**	0.190	0.245	0.302	0.100	0.048*	0.374	0.410
Cover crop (C)	0.938	0.473	0.110	0.089	0.002**	0.000***	0.000***	0.000***
Y x L	0.000***	0.000***	0.000***	0.013*	0.000***	0.022*	0.934	0.424
Y x T	0.007**	0.851	0.058	0.010*	0.808	0.222	0.240	0.008**
L x T	0.040*	0.144	0.151	0.243	0.599	0.430	0.057	0.313
Y x C	0.472	0.854	0.115	0.434	0.013*	0.001**	0.065	0.028*
L x C	0.787	0.298	0.207	0.116	0.206	0.394	0.084	0.000***
T x C	0.856	0.433	0.491	0.817	0.987	0.745	0.876	0.293
Y x L x T	0.189	0.342	0.156	0.363	0.193	0.538	0.097	0.304
Y x L x C	0.522	0.393	0.775	0.593	0.497	0.578	0.459	0.627
Y x T x C	0.817	0.933	0.575	0.808	0.197	0.982	0.224	0.191
L x T x C	0.057**.**	0.313	0.616	0.432	0.126	0.927	0.527	0.364
Y x L x T x C	**0.481**	**0.539**	**0.120**	**0.119**	**0.447**	**0.995**	**0.927**	0.356

Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, and 0.05, and 0.1 level.

SOYBEAN BIOMASS- AND GRAIN-N

Soybean biomass-N (stover) was affected by year and the year x location interaction while grain-N was affected by year, location and their interaction; neither biomass-n nor grain-N were affected by cover crop strategies (Table 3.3).

When pooled over tillage and cover crop strategy, soybean grain-N was highest at Lamberton in 2017 (209 lb/ac – 234 kg ha^{-1} –) compared to 2018 (199 lb/ac – 223 kg ha^{-1} –) and 2019 (186 lb/ac – 145 kg ha^{-1} –). Soybean grain-N was similar at Waseca among years: 174 kg ha^{-1} (155 lb/ac), 170 kg ha^{-1} (152 lb/ac), and 162 kg ha^{-1} (145 lb/ac) in 2017, 2018, and 2019, respectively. Pooled averages of soybean grain-N over years were similar across cover crop strategies, ranging from 195 (174 lb/ac) to 202 kg ha^{-1} (180 lb/ac) at Lamberton and 167 (149 lb/ac) to 170 kg ha^{-1} (152 lb/ac) at Waseca (Figure 3.2).



(a) (b)

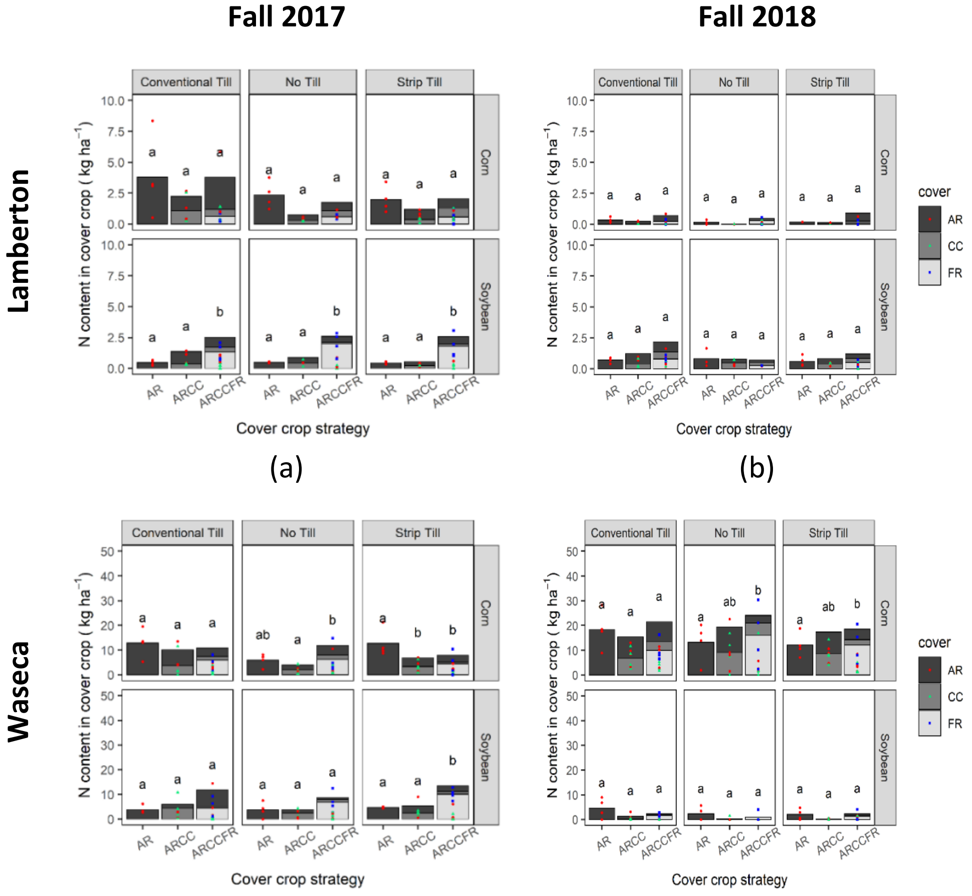
(c) (d)

Figure 3.2 Soybean biomass- and grain-N at SWROC near Lamberton, MN and SROC, Waseca, MN from 2017 to 2019. Bars followed by the same letters are not significantly different at P ≤ 0.05 within each tillage practice each year. Error bars represent SEM (n=4), and dots represent data points. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish, and NC = no cover (control).

There is limited research information regarding N in soybean grain and biomass as affected by cover crops. A study conducted in Iowa reports no effect of cover crops and tillage practices in N accumulation in soybean biomass (Karlen & Doran, 1991). More recently, another study in Iowa reported no effect of cover crops in N accumulation in soybean biomass measured during the growing season (Basche et al., 2016). Such studies included winter cover crops seeded early in the growing season and produced an average of 1455 lb DM/ac (1.63 Mg DM ha^{-1}) in the spring. Our study included late-interseeded winterkilled cover crops and produced marginal biomass of around 65 lb DM/ac (0.073 Mg DM ha^{-1}) on average. The limited biomass observed in this study can explain undiscernible differences among cover crop strategies in soybean N accumulation in the soybean grain and biomass.

BIOMASS-N IN COVER CROPS

Cover crops biomass-N within corn was affected by location, cover crop strategy, year x location, and year x cover crop strategy interactions. Cover crops biomass-N within soybean was affected by year, location, tillage, cover crop strategy, and the year x cover crop strategy interaction (Table 3.3). The amounts of cover crop biomass-N, however, was marginal within each primary crop.



(a)

(b)

(c)

(d)

Figure 3.3 Cover crop biomass-N in fall 2017 and 2018 at SROC, Waseca, MN, USA. Different colors within a bar represent different species within a mix, and dots represent data points (n=4 for each cover crop species within each cover crop strategy). Bars followed by the same letters are not significantly different at P ≤ 0.05 within each tillage practice each year. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish.

When pooled over corn, cover crops biomass-N at Lamberton was 1.8 lb/acre (2 kg ha^{-1}) and 0.7 lb/acre (0.81 kg ha^{-1}) in 2017 and 2018, respectively. Within soybean plots, cover crops in Lamberton accumulated 1 lb/acre (1.18 kg ha^{-1}) in 2017 and 0.20 lb/acre (0.22 kg ha^{-1}) in 2018. Cover crops biomass-N within both, corn and soybean was significantly higher at Waseca compared to Lamberton in both years: 8 lb/acre (9.22 kg ha^{-1}) in 2017 and 16 lb/acre (18 kg ha^{-1}) in 2018 following corn and 6 lb/acre (6.73 kg ha^{-1}) and 1.6 lb/acre (1.83 kg ha^{-1}) in 2017 and 2018 following soybean. Studies conducted in the U.S. upper Midwest have reported comparatively higher biomass-N from cover crops interseeded within corn and soybean than the results reported in this study (De Bruin et al., 2005; Noland et al., 2018; Strock et al., 2004; Wilson et al., 2013); however, the cover crop used in those studies is mostly the overwintering CR.

In this study, cover crop biomass-N varied among strategy in both corn and soybean (Table 3.3). In corn, the 3-way mix of ARCCFR accumulated more N (8.3 lb/acre – 9.25 kg ha^{-1} –) than ARCC (6 lb/acre – 6.57 kg ha^{-1} –) and AR monoculture (6.5 lb/acre – 7.25 kg ha^{-1} –) when pooled over years and locations. In soybean, biomass-N was 3.6, 2.3, and 2.0 lb/acre (3.98, 1.56, and 2.28 kg ha^{-1}) in ARCCFR, ARCC, and AR, respectively. In Waseca in 2018, forage radish established well within corn, which could have contributed to more biomass-N than ARCC and AR monoculture. Forage radish is an excellent N scavenger, but is comparatively more sensitive to winter injury than AR and CC (SARE, 2007) (Figure 3.3).

C:N RATIO IN COVER CROP BIOMASS

Cover crop C:N ratio within corn was affected by location and cover crop strategy and within soybean by year, location, cover crop strategy, and their interaction (Table 3.3). At Lamberton the 2-year average C:N ratio among cover crops was ~10:1 within corn and ~10:1 in 2017 and 11:1 in 2018 within soybean. At Waseca within corn in 2017, the pooled C:N ratio of cover crops were 12, 13, and 11 for AR, ARCC, and ARCCFR, respectively, while in 2018, the pooled C:N ratio of AR, ARCC and ARCCFR were 13, 13, and 10, respectively. Within soybean, C:N ratio in AR, ARCC, and ARCCFR were 11, 14, and 10, respectively, in 2017; and 14, 14, and 10, respectively, in 2018.

The C:N ratio of cover crops was not affected by tillage practices. At Lamberton, the only significant difference observed was between AR and ARCC strategies within ST in 2017 (Figure 3.4). However, at Waseca, differences on C:N of cover crops were observed within 2017 soybean and 2018 corn. The ARCC strategy, a mixture of a grass and a legume species, had a significantly higher C:N ratio than AR and ARCCFR within the three tillage practices (Figure 3.4). The pooled averages of AR monoculture, ARCC, and ARCCFR over site-years was 11, 12, and 10, respectively. The 2-way mix ARCC consistently had higher C:N ratio than the other strategies, even though it produced lower biomass than ARCCFR and AR monoculture throughout the study. Studies have on C:N ratio of cover crop mixtures are reported to be higher than that of monocultures. Finney et al. (2016) reported that the mixture of eight cover crops had higher C:N ratio than most monocultures. However, Kuo & Jellum (2002) reported from a 4-yr study that a mixture of AR and hairy vetch had more C:N ratio than AR monoculture. Our results of higher C:N ratio in ARCC as compared to AR monoculture corroborate the results of such study.

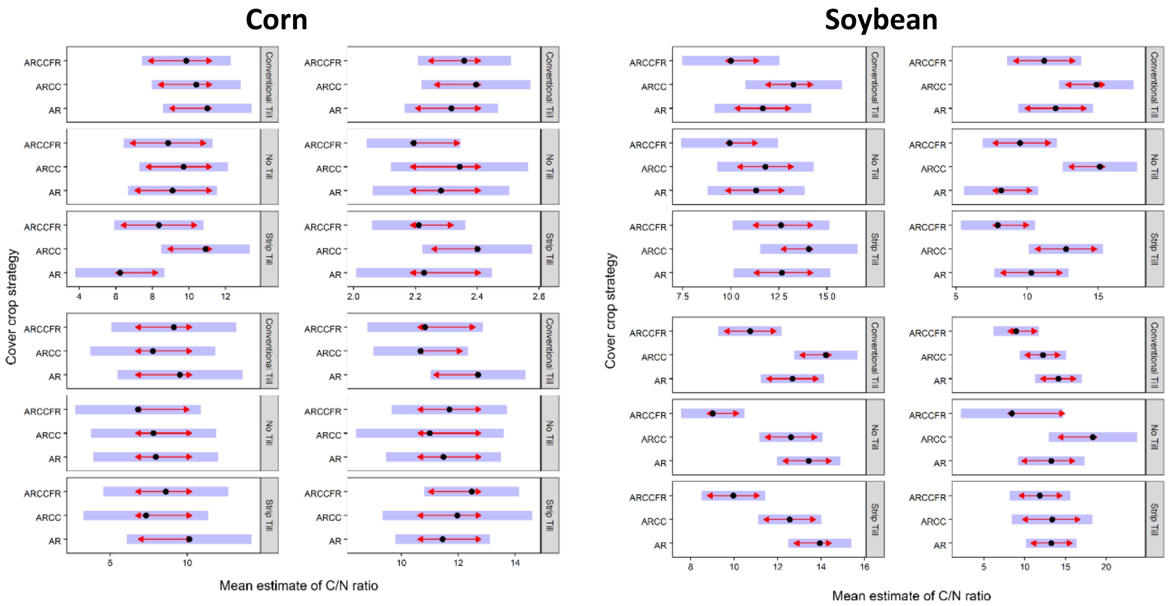


Figure 3.4 Average C:N ratio among cover crop strategies within three tillage practices in corn and soybean in 2017 and 2018 at SWROC near Lamberton, MN and SROC Waseca, MN. Black dots represent estimated marginal means, and blue bars are 95% confidence intervals. Within each tillage practice, red arrows overlapping among AR, ARCC, and ARCCFR are not significantly different at $p \leq 0.05$. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish.

SOIL-N WITHIN CORN AND SOYBEAN PLOTS

Residual soil NO_3-N was affected by location and year at both 0-6 and 6-12 inch soil layers. Location x year interaction was observed during both, spring and fall seasons and depth, suggesting that NO_3-N in this study was affected by environmental conditions (Table 3.4).

A separate analysis of residual soil NO_3-N at Lamberton revealed the effect of tillage x cover crop strategy interaction within corn plots at the time of seeding cover crops in 2017 at 0-15 cm layer (Table 3.5); however, cover crops were not seeded at the time of the sampling. In another sampling event at Lamberton in the fall of 2018, tillage practice affected soil NO_3-N at 0-15 cm layer within soybean plots; within a tillage practice, the pooled average across cover crop strategies was 4.68 kg ha^{-1} in CT, 4.12 kg ha^{-1} in NT, and 4.76 kg ha^{-1} in ST (Table 3.5). However, no effect of tillage or cover crop strategy was found in any sampling event at 15-30 cm layer in Lamberton during the study (Table 3.6).

Table 3.4 Significance of fixed effects on residual soil NO_3-N in spring before planting corn and soybean in 2018, and 2019 at Lamberton and Waseca, MN, and before frost in the fall in 2017 and 2018.

Source of variation	**0-6 inch**		**Fall 0-6 inch**		**Spring 6-12 inch**		**Fall 6-12 inch**	
	Corn	*Soybean*	*Corn*	*Soybean*	*Corn*	*Soybean*	*Corn*	*Soybean*
Year (Y)	0.000***	0.000***	0.000***	0.000***	0.007**	0.002**	0.002**	0.000***
Location (L)	0.970	0.563	0.000***	0.000***	0.000***	0.897	0.001**	0.167
Tillage (T)	0.623	0.092.	0.381	0.291	0.235	0.050.	0.916	0.190
Cover crop (C)	0.492	0.720	0.360	0.843	0.889	0.778	0.113	0.657
Y x L	0.000***	0.000***	0.000***	0.012*	0.000***	0.000***	0.000***	0.000***
Y x T	0.527	0.002**	0.391	0.618	0.429	0.027*	0.908	0.958
L x T	0.186	0.045*	0.788	0.410	0.908	0.003	0.666	0.672
Y x C	0.709	0.855	0.515	0.496	0.178	0.824	0.095.	0.418
L x C	0.996	0.134	0.111	0.887	0.947	0.835	0.635	0.952
T x C	0.941	0.901	0.971	0.671	0.526	0.701	0.737	0.864
Y x L x T	0.021*	0.050.	0.725	0.197	0.469	0.306	0.906	0.774
Y x L x C	0.153	0.411	0.935	0.459	0.774	0.728	0.473	0.988
Y x T x C	0.892	0.505	0.566	0.350	0.253	0.875	0.705	0.142
L x T x C	0.423	0.557	0.075.	0.997	0.098.	0.565	0.709	0.860
Y x L x T x C	0.521	0.729	0.634	0.953	0.532	0.938	0.989	0.075.

Significance of fixed effects (P > F) on the response: residual soil NO_3-N in spring and fall at 0-15 and 15-30 cm at Lamberton and Waseca, MN. Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level.

Table 3.5 Significance of fixed effects (P > F) on residual soil NO3-N (kg ha-1) in the 0-6 inch soil layer in spring before planting in 2018 and 2019, before late-seeding cover crops in 2017 and 2018, and in the fall before frost in 2017, 2018, and 2019 in SWROC near Lamberton, MN, USA.

Tillage	Cover crop strategy	2017				2018						2019			
		Seeding		Fall		Spring		Seeding		Fall		Spring		Fall [§]	
		Corn	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*
		NO_3-N kg ha^{-1}													
CT	AR	1.89	1.33	5.53	4.55	8.87	16.52	3.20	1.17	5.56	4.53	5.29	3.93	8.97	3.31
	ARCC	5.74	0.67	5.02	5.35	11.98	13.15	2.29	0.87	4.68	4.88	6.41	4.15	10.92	3.31
	ARCCFR	3.02	0.92	9.36	4.61	11.70	11.97	6.21	1.01	5.99	4.98	5.25	3.39	14.04	4.68
	NC	4.75	1.26	9.89	4.47	10.90	13.36	5.34	0.92	7.44	4.31	4.67	4.87	15.60	4.29
NT	AR	11.02**b**	0.78	7.48	6.00	13.12	15.04	2.45	0.70	4.78	2.78**a**	2.98	4.05	10.92	3.12
	ARCC	6.24**ab**	1.30	4.24	7.58	10.45	13.81	4.32	1.02	4.71	4.80**b**	4.39	5.03	9.75	2.14
	ARCCFR	2.2 **a**	0.66	5.07	6.16	13.48	8.67	1.58	1.00	6.61	4.12**ab**	3.94	4.09	9.75	2.92
	NC	8.33**ab**	0.85	6.38	5.28	16.14	10.08	4.74	0.79	4.79	3.42**ab**	3.29	4.05	6.63	2.14
ST	AR	10.87	2.91	4.82	4.64	17.08	13.05	3.09	1.21	3.90	5.26	4.91	4.77	21.25	2.73
	ARCC	4.9	1.20	5.91	5.61	12.29	15.10	4.95	0.89	5.03	4.36	4.59	3.98	17.94	3.12
	ARCCFR	9.04	1.12	4.34	5.17	17.71	12.58	2.28	0.87	6.59	4.66	4.97	3.94	10.14	3.90
	NC	5.06	1.80	5.29	5.59	16.34	13.05	4.38	0.83	6.10	4.76	4.47	3.79	26.91	4.87
Mean		6.08	1.18	6.11	5.41	13.33	13.03	3.73	0.94	5.51	4.40	4.59	4.17	13.56	13.38
Tillage (T) [¥]		0.32	0.12	0.24	0.23	0.231	0.409	0.54	0.92	0.60	0.03*	0.17	0.93		
Cover crop (C)		0.48	0.23	0.27	0.61	0.611	0.104	0.18	0.88	0.08	0.35	0.39	0.87		
T x C		0.03*	0.31	0.11	0.98	0.983	0.661	0.11	0.79	0.60	0.80	0.17	0.91		

[¥] Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level. [§] Residual soil NO_3-N not analyzed for Fall, 2019, due to lack of replicates. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR +CC + forage radish, and NC = no cover (control).

Table 3.6 Significance of fixed effects (P > F) on residual soil NO3-N (kg ha-1) in the 6-12 inch soil layer in spring before planting in 2018 and 2019, before late-seeding cover crops in 2017 and 2018, and in the fall before frost in 2017, 2018, and 2019 in SWROC near Lamberton, MN, USA.

Tillage	Cover crop strategy	2017				2018						2019			
		Seeding		Fall		Spring		Seeding		Fall		Spring		Fall [§]	
		Corn	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*
								NO_3-N kg ha^{-1}							
CT.	AR	2.62	1.3	5.97	4.99	6.14	7.63	1.39	0.59	4.46	3.3	5.74	6.58	6.83	3.51
	ARCC	3.95	1.46	6.4	4.25	6.35	6.65	2.05	0.59	4.12	3.12	5.85	4.43	7.22	2.93
	ARCCFR	3.06	1.41	6.98	5.29	4.45	8.08	2.14	0.59	5.39	2.97	5.11	3.98	8.97	5.66
	NC	4.05	1.44	6.84	7.12	6.82	6.38	1.99	0.63	6.44	3.16	4.01	5.32	10.14	4.68
NT	AR	4.53	1.22	4.01	5.65	5.1	6.57	2.49	0.59	4.66	2.71	3.86	4.82	7.22	2.15
	ARCC	4.55	0.8	5.24	3.88	4.59	5.56	5.5	0.58	5.23	2.31	5.66	5.49	10.53	2.15
	ARCCFR	2.65	0.87	5.83	5.19	5.36	5.28	1.57	0.63	6.37	2.49	4.84	6.68	10.73	2.54
	NC	2.98	0.92	5.95	3.91	5.74	4.7	2.83	0.59	5.35	2.71	4.42	4.81	9.95	2.73
ST	AR	8.29	0.96	5.4	4.03	6.37	7.9	2.24	0.71	3.73	4.00	5.04	3.34	15.41	2.93
	ARCC	4.27	2.53	4.38	5.00	5.31	8.28	1.3	0.7	4.17	2.54	4.41	3.94	17.94	1.95
	ARCCFR	5.67	1.06	5.21	4.18	4.66	7.04	1.12	0.77	6.83	2.98	6.12	4.16	9.75	2.54
	NC	3.79	1.7	5.17	3.63	5.33	6.78	1.27	0.59	4.25	3.31	6.35	4.46	13.65	3.12
Mean		4.2	1.3	5.61	4.76	5.51	6.73	2.15	0.63	5.08	2.96	5.11	4.83	10.6	3.07
Tillage (T) [¥]		0.45	0.22	0.21	0.36	0.52	0.23	0.35	0.32	0.80	0.15	0.39	0.28		
Cover crop (C)		0.63	0.72	0.20	0.86	0.29	0.47	0.51	0.65	0.09	0.31	0.75	0.98		
T x C		0.36	0.51	0.45	0.21	0.66	0.95	0.36	0.61	0.71	0.91	0.15	0.53		

[¥] Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level. [§] Residual soil NO_3-N not analyzed for fall, 2019 due to lack of replicates. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR +CC + forage radish, and NC = no cover (control).

Table 3.7 Significance of fixed effects (P > F) on residual soil NO_3-N (kg ha^{-1}) in the 0-6 inch soil layer in spring before planting in 2018 and 2019, before late-seeding cover crops in 2017 and 2018, and in the fall before frost in 2017, 2018, and 2019 in SROC, Waseca, MN, USA.

Tillage	Cover crop strategy	2017				2018						2019			
		Seeding		Fall		Spring		Seeding		Fall		Spring		Fall [§]	
		Corn	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*
		NO_3-N (kg ha^{-1})													
CT	AR	7.49	9.74	8.40	10.32	6.39	8.72	3.07	5.35	13.45	16.19	8.00	8.26	10.34	14.63
	ARCC	7.91	11.48	9.66	10.70	5.24	6.76	4.74	4.96	14.16	14.11	8.27	9.69	15.60	16.58
	ARCCFR	8.74	7.08	6.26	8.27	7.59	8.30	3.72	4.56	13.75	12.10	8.16	11.25	14.43	18.33
	NC	13.62	6.05	5.78	5.47	7.61	8.04	4.58	4.11	12.62	14.34	8.88	6.34	11.70	17.75
NT	AR	7.70	5.69	4.86	6.69	5.59	2.49	3.65	2.19	12.64	12.19	9.77	8.14	12.87	14.43
	ARCC	7.16	8.43	5.03	7.74	6.98	2.96	2.90	2.03	15.89	10.92	9.68	8.57	7.41	17.75
	ARCCFR	7.68	8.83	4.34	7.12	7.18	2.76	2.76	2.11	14.72	9.93	10.33	8.61	14.63	22.04
	NC	10.62	7.50	8.20	7.74	6.01	3.86	3.92	1.88	16.78	10.78	11.25	7.89	6.83	17.36
ST	AR	10.92	5.09	8.22	6.20	5.34	5.48	1.45	3.12	12.66	14.42	9.92	9.10	22.43	6.63
	ARCC	10.44	8.83	6.90	5.66	7.17	8.78	3.10	3.64	12.68	13.43	8.90	9.43	13.65	12.87
	ARCCFR	7.74	7.90	6.06	7.00	5.87	8.17	4.97	3.16	13.63	13.93	9.99	9.22	13.07	16.38
	NC	15.71	9.15	6.85	7.16	4.74	7.26	2.45	4.25	13.09	14.43	10.15	9.82	13.65	7.22
Mean		9.64	7.98	6.71	7.51	6.31	6.13	3.44	3.45	13.83	13.06	9.44	8.86	13.05	15.16
Tillage (T) [¥]		0.70	0.85	0.34	0.47	0.57	0.015	0.802	0.38	0.74	0.51	0.460	0.54		
Cover crop (C)		0.13	0.48	0.61	0.93	0.64	0.518	0.148	0.99	0.66	0.24	0.618	0.39		
T x C		0.97	0.61	0.55	0.71	0.45	0.408	0.453	0.99	0.73	0.93	0.994	0.53		

[¥] Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level. [§] Residual soil NO_3-N not analyzed for Fall, 2019, due to lack of replicates. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish, and NC = no cover (control).

Table 3.8 Significance of fixed effects (P > F) on residual soil NO_3-N (kg ha^{-1}) in the 6-12 inch soil layer in spring before planting in 2018 and 2019, before late-seeding cover crops in 2017 and 2018, and in the fall before frost in 2017, 2018, and 2019 in SROC, Waseca, MN, USA.

Tillage	Cover crop strategy	2017				2018						2019			
		Seeding		Fall		Spring		Seeding		Fall		Spring		Fall §	
		Corn	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*	*Corn*	*Soy*
		NO_3-N (kg ha^{-1})													
CT	AR	6.13	8.94	5.4	7.19	8.66	10.49	3.9	5.74	13.84	15.56	10.91	10.32	15.02	11.9
	ARCC	6.93	8.32	6.88	9.32	6.34	10.48	4.05	3.08	15.02	15.66	9.05	10.46	16.58	17.55
	ARCCFR	8.50	4.8	5.34	6.57	8.14	11.47	2.52	3.53	12.09	15.25	11.11	11.11	17.16	16.97
	NC	12.19	5.73	5.23	4.45	9.10	10.35	3.75	6.95	14.71	15.44	10.16	10.54	8.97	26.13
NT	AR	4.90	5.7	5.28	4.59	5.97	3.27	2.97	1.95	14.85	11.97	10.14	8.41	9.75	18.72
	ARCC	5.60	6.79	4.89	4.8	7.14	3.71	3.03	1.39	19.92	10.71	11.69	9.27	6.63	18.72
	ARCCFR	6.25	7.65	4.41	5.98	6.85	2.85	3.04	2.02	14.41	10.21	10.60	9.85	11.12	17.36
	NC	8.19	4.8	7.07	7.54	5.67	3.31	3.29	1.9	16.26	11.49	10.35	6.85	6.83	16.19
ST	AR	9.05	4.4	5.68	6.97	7.04**ab**	8.33	1.77	2.85	11.65	12.48	9.39	9.77	16.58	9.95
	ARCC	7.56	7.85	4.28	5.48	8.96**b**	9.57	2.51	3.35	15.33	13.11	11.61	10.18	14.43	14.43
	ARCCFR	6.97	5.57	6.49	7.19	5.67**a**	6.81	2.76	3.32	13.55	17.01	10.85	8.08	15.21	15.99
	NC	12.5	6.05	7.12	5.93	7.99**ab**	8.1	3.5	3.29	13.89	14.18	10.00	9.52	14.04	5.85
Mean		7.89	6.38	5.67	6.33	7.29	7.39	3.09	3.28	14.62	13.58	10.48	9.53	12.69	15.81
Tillage (T) ¥		0.62	0.82	0.86	0.57	0.31	0.019*	0.82	0.36	0.491	0.285	0.927	0.218		
Cover crop (C)		0.06	0.63	0.68	0.93	0.77	0.83	0.76	0.56	0.072.	0.845	0.887	0.522		
T x C		0.93	0.72	0.57	0.20	0.04*	0.98	0.86	0.79	0.856	0.299	0.768	0.103		

¥ Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level. § Residual soil NO_3-N not analyzed for Fall, 2019, due to lack of replicates. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR +CC + forage radish, and NC = no cover (control).

At Waseca site, residual soil NO_3-N at 0-6 inch soil layer was not affected by any treatment at any sampling event (Table 3.7). However, at the 6-12 inch soil layer, tillage significantly affected residual soil NO_3-N in spring 2018 within soybean plots, where corn was planted in 2017 (Table 3.8). Conventionally tilled plots had 9.55 lb/ac (10.7 kg ha^{-1}) residual soil NO_3-N compared to ~3.0 lb/ac (3.3 kg ha^{-1}) in NT and 7.3 lb/ac (8.2 kg ha^{-1}) in ST. Residual NO_3-N was significantly higher in 2018 as compared to 2017 at both depths in Waseca.

SOIL-N DYNAMICS IN CORN-SOYBEAN ROTATIONS WITH COVER CROPS

CHANGE IN NO_3-N FROM COVER CROP SEEDING TO FALL FROST

At 0-15 cm layer, change in soil NO_3-N concentration from cover crop seeding to fall frost was significantly different between corn and soybean plots only (Table 3.9). Soil NO_3-N concentration was greater in the fall than at the time of seeding. This implies that the N uptake by cover crop biomass in the period after seeding until the fall frost was not enough to affect NO_3-N at 0-15 cm layer. However, soil NO_3-N movement downwards is possible because of mass flow of soil water is the carrier of NO_3-N **Error! Bookmark not defined.**. Since more precipitation occurred at the time of seeding than at fall frost, more NO_3-N could have leached downward in the soil profile. Similarly, NO_3-N at the 15-30 cm soil layer was greater in the fall as compared to the time of seeding (Figure 3.5).

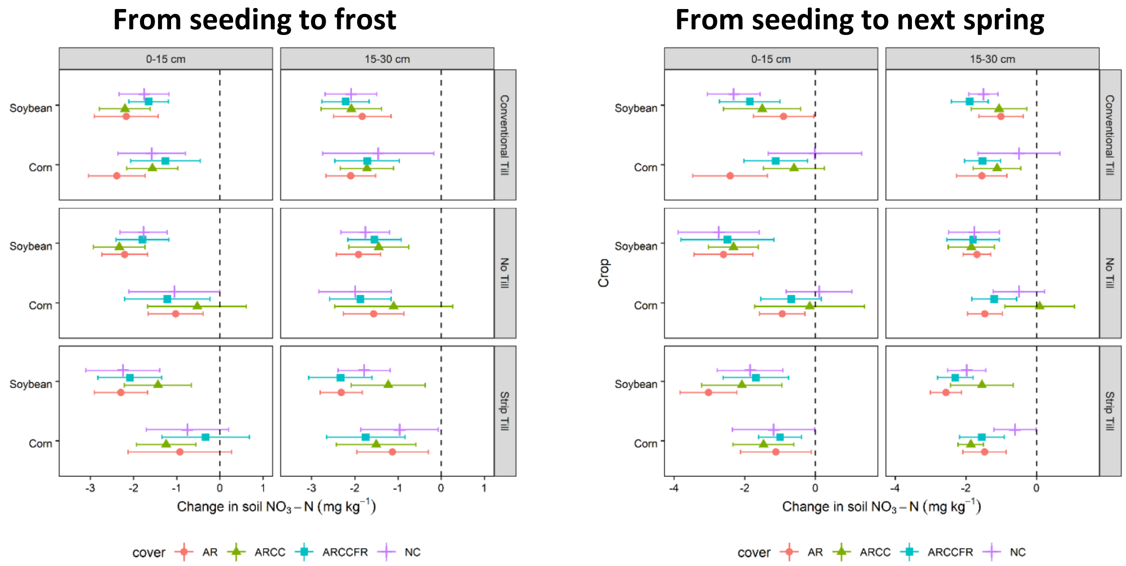


Figure 3.5 Dynamics of soil NO_3-N concentration from seeding to frost and seeding to next spring at 0-6 and 6-12 (0-15 and 15-30 cm) inch layers. AR = annual ryegrass, CC = crimson clover, FR = forage radish, and NC = no-cover (control) within three tillage practices during the 2017 and 2018 growing seasons in SWROC near Lamberton, and SROC, Waseca, MN, USA. Negative values (left to the vertical dashed line) denote higher NO3-N concentration in the fall than at seeding time. Points represent mean values, and lines represent SEM (n=16). Lines that do not intersect the vertical dashed line are significantly different from zero.

Table 3.9 Significance of fixed effects on the difference in residual soil NO_3-N from seeding cover crops to fall and from seeding cover crops to spring before planting in the next season. Values are averaged over two seasons of cover cropping in Lamberton and Waseca, MN, USA.

Source of variation	Difference in residual soil NO_3-N (Δ soil NO_3-N)			
	Δ soil NO_3-N from seeding to fall		Δ soil NO_3-N from seeding to spring	
	0-6 inches	*6-12 inches*	*0-6 inches*	*6-12 inches*
Crop	0.000***	0.108	0.000***	0.003**
Tillage practice (T)	0.861	0.941	0.912	0.670
Cover crop strategy (C)	0.566	0.54	0.659	0.172
Crop x T	0.119	0.487	0.136	0.305
Crop x C	0.994	0.937	0.543	0.456
T x C	0.963	0.875	0.997	0.964
Crop x T x C	0.675	0.624	0.488	0.482

Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level.

CHANGE IN NO_3 -N FROM COVER CROPS SEEDING TO SPRING

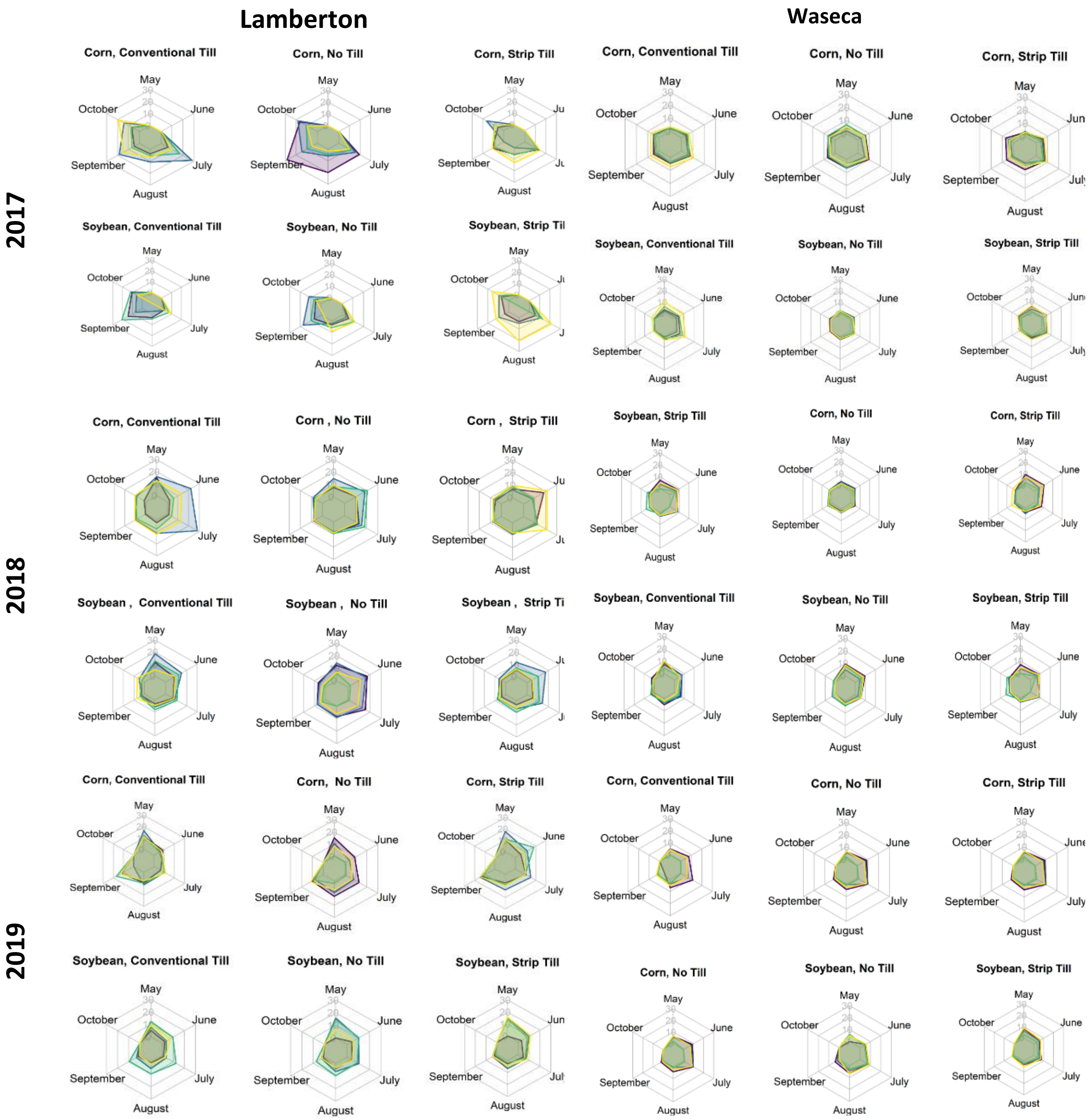
At the 0-15 cm layer, changes in soil NO_3-N from cover crop seeding in late summer to early spring differed only between corn and soybean plots (Table 3.9). Soil NO_3-N was greater at cover crop termination in the spring than at seeding. Similarly, at the 15-30 cm layer, soil NO_3-N was greater at cover crop termination in spring than at seeding in late summer (Figure 3.5). Difference in soil NO_3-N were larger in spring than in the fall, with greater concentration in the spring as compared to fall.

SOIL SOLUTION N WITHIN CORN AND SOYBEAN PLOTS

The yearly average of NO_3-N concentration in the soil solution was higher at Lamberton than at Waseca for each study year. Average NO_3-N concentration in the soil solution at Lamberton during the growing season was 10.2, 12.36, and 9.69 mg kg^{-1} in 2017, 2018, and 2019, respectively, and at Waseca was 5.31, 5.69, and 7.52 mg kg^{-1} in 2017, 2018 and 2019, respectively. Data were not statistically analyzed due to the lack of replicates. Monthly averages of NO_3-N concentration in the soil solution at Lamberton and Waseca during the growing season of 2017, 2018, and 2019 are displayed as radar charts (Figure 3.6).

NET N MINERALIZATION DURING THE CORN AND SOYBEAN GROWING SEASON

At Lamberton site, soil N mineralization varied with tillage practice within soybean plots in 2018. Tillage practice and date interactions were significant in every analysis, except within soybean plots in 2019. A 3-way interaction of tillage, cover crop strategy, and date was observed in 2018 within soybean plots. In 2019, date significantly affected net N mineralization within corn.



Corn, Conventional Till
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Corn, Strip Till
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Soybean, Strip Till

Figure 3.6 Concentration of NO_3-N (mg Kg^{-1}) in the soil solution collected at 40 inches depth during the growing season (May-Oct) of 2019 in SROC, Waseca, MN. Values are monthly averages. AR = annual ryegrass; ARCC = AR+ crimson clover; ARCCFR = AR + CC + forage radish, NC = no cover (control).

At Waseca site, tillage practice significantly affected N mineralization during the growing season in 2018, only. Nitrogen mineralization differed between dates in every study at Waseca. Similar to Lamberton, tillage and date interaction was observed in both 2018 and 2019 within corn and soybean plots. A 3-way interaction of tillage practice, cover crop strategy, and date was observed only in the 2019 soybean plot (Table 3.10). These findings agree with our results showing poor cover crops growth performance. Because of the extreme cold conditions during winter in the region, the little N accumulated by the cover crops begins mineralization early in the spring.

Table 3.10 Significance of fixed effects (P > F) on net N mineralization in the growing season at Lamberton and Waseca, MN.

Source of variation	**Net N mineralization (μg g^{-1} d^{-1})**							
	Lamberton				Waseca			
	2018		*2019*		*2018*		*2019*	
	Corn	Soybean	Corn	Soybean	Corn	Soybean	Corn	Soybean
T	0.140	0.033*	0.135	0.342	0.000***	0.000***	0.338	0.237
C	0.715	0.108	0.932	0.127	0.127	0.137	0.356	0.329
D	0.193	0.083	0.000***	0.866	0.000***	0.049*	0.000***	0.000***
T x C	0.558	0.027*	0.725	0.179	0.417	0.311	0.500	0.397
T x D	0.000***	0.000***	0.000***	0.078.	0.004**	0.000***	0.008**	0.000***
C x D	0.071	0.120	0.660	0.522	0.003**	0.002**	0.070.	0.038*
T x C x D	0.424	0.005**	0.426	0.325	0.639	0.160	0.248	0.034*

Numbers followed by ***, **, *, and a single dot within a single column are significant at 0.001, 0.01, 0.05, and 0.1 level. Data were analyzed for each location, year, and crop separately for simplicity.

Net N mineralization in Lamberton in 2018 was negative mostly during the growing season within both corn and soybean plots, suggesting more N was immobilized than mineralized. However, in 2019 net N mineralization showed a decreasing trend over time in the growing season within corn plots. No specific trend was observed within soybean plots, but net N mineralization was positive overall during the whole season. At the Waseca site, the net N mineralization was positive in both corn and soybean plots, except for the first date in late May 2018. Similar trend was observed during the 2019 growing season at Waseca, where net N mineralization decreased as the growing season progressed. Consistently, more N mineralization was observed in corn plots than soybean plots during the study period (Figure 3.7).

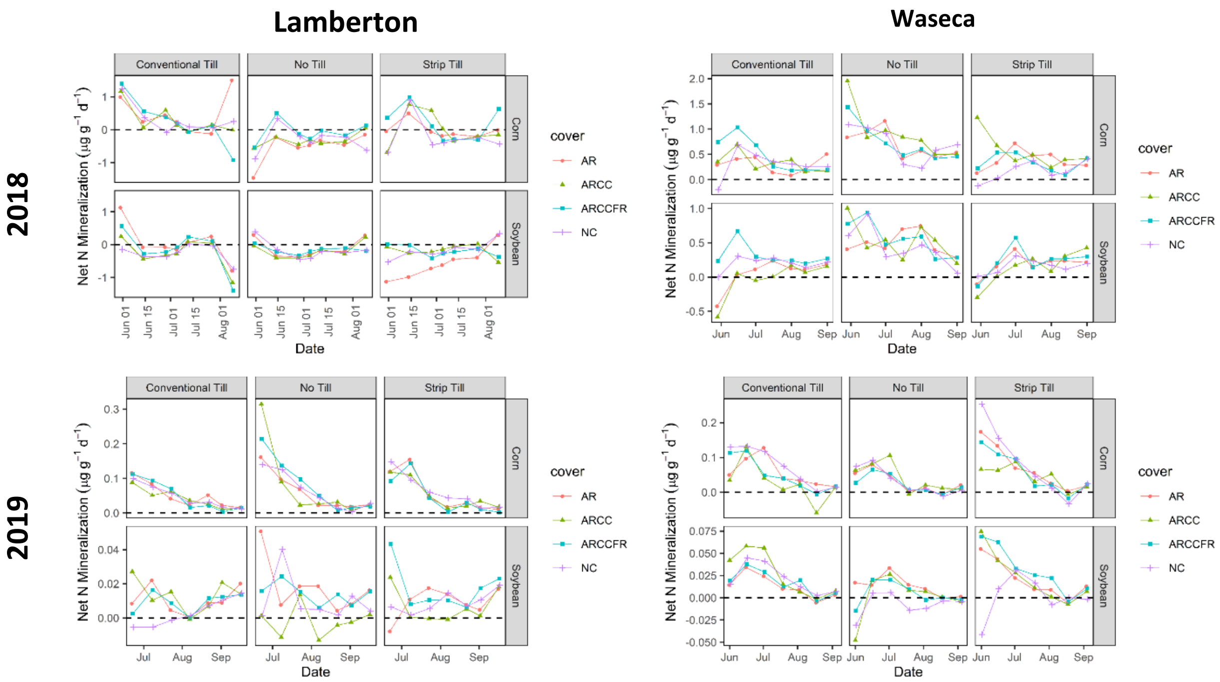


Figure 3.7. Net N mineralization during the 2018 and 2019 growing seasons at SWROC near Lamberton and SROC, Waseca, MN. Values below and above the horizontal dotted line represent N immobilization and N mineralization, respectively. AR = annual ryegrass, ARCC = AR + crimson clover, ARCCFR = AR + CC + forage radish, and NC = no cover (control).

CONCLUSIONS

This study was conducted to advance our understanding on the effect of late-interseeded winterkilled cover crops on N dynamics in corn-soybean rotation under three tillage practices.

After two seasons of cover cropping, differences in soil organic matter were observed between cover crop strategies and tillage practice at the Lamberton site. Corn and soybean biomass- and grain-N was not affected by tillage practice or cover crop strategy. Variation in crops N biomass- and grain-N varied significantly by location, year, and location x year interactions, suggesting that environment affected N uptake more than tillage practice or cover crop strategy.

Cover crop biomass-N varied highly from year to year, and it was consistently higher in the 3-way mix of ARCCFR was than in the 2-way mix of ARCC and AR monoculture throughout the study. This is consistent with the amount of biomass produced among the cover crop strategies. On the other hand, C:N among cover crop strategies differed significantly, with ARCC consistently having higher C:N as compared to ARCCFR and AR. This suggests that C:N may not necessarily be affected by diversity richness at early cover crops growth.

Cover crop strategy and tillage practice seemed to have no effect on the residual NO_3-N at both locations and study years. Variations in residual NO_3-N were primarily driven by year, location, and their interactions. More soil NO_3-N concentration was observed in the fall and in the next spring (before planting primary crops) than at the time of seeding cover crops late in the season, which could have resulted from mineralization of primary crop residues.

Inferences on the NO_3-N concentration in the soil solution were not made because of the lack of consistent replicates. Still, a visual representation of monthly NO_3-N concentrations did not reveal any consistent patterns among cover crop strategies within tillage practice in either primary crop.

The rate of net N mineralization decreased throughout the growing season in both locations and years, and the N mineralization potential within corn plots was higher than within soybean plots.

Although late winterkilled, late-interseed cover crops have the potential to produce biomass in the fall in the upper Midwest U.S., they may not produce ecological benefits. Therefore, the ecological benefits of winterkilled, late-interseeded cover crops may not outweigh the input costs associated with such strategy.

Winterkilled cover crop research should be focused on early-interseeding in the primary crops growing season, rather than late-interseeding. For late-interseeding, overwintering cover crops may be a viable option in the cold upper Midwest U.S. conditions.

CHAPTER 4 – COVER CROPS AT MULTIPLE LOCATIONS: EFFECTS OF WINTERKILLED AND WINDER HARDY COVER CROPS ON PRODUCTIVITY OF CORN ACROSS MN

ABSTRACT

The incorporation of cover crops into the corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation in the U.S. upper Midwest may improve sustainability. Long, cold winters in the region make identifying successful cover crop species and management practices a challenge. Two cover crop experiments were conducted in Minnesota from fall 2016 through spring 2019 to examine their effect on productivity of corn. The studies were located in Grand Rapids, Lamberton, and Waseca. Annual ryegrass (*Lolium multiflorum* L.) and cereal rye (*Secale cereale* L.) were evaluated as monocultures and in mixtures with crimson clover (*Trifolium incarnatum* L.) and forage radish (*Raphanus sativus* L.). At all three locations cover crop were interseeded at V4 to V6 (four- to six-leaf collar) corn, thereafter referred to as early-interseeded, and R5 to R6 (dent to physiological maturity) corn, thereafter referred to as late-interseeded. Differences in cover crop canopy cover and biomass of early-interseeded cover crops were observed by fall frost at all locations in 2017 and at Grand Rapids in 2018. Early-interseeded cover crops did not affect corn aboveground biomass or yield. Differences in canopy cover and biomass of late-interseeded cover crops were observed at Waseca in 2018. Additional accumulated growing-degree days in fall 2018 did not translate into increased cover crop canopy coverage of late-interseeded cover crops. Cover crop canopy cover and biomass at termination before planting corn, soil moisture at corn planting as well as corn aboveground biomass and yield were not affected by late-interseeded cover crops. We attribute these results to limited cover crop growth. These results highlight the potential of a variety of cover crop strategies interseeded into corn in the U.S. upper Midwest. Efforts to fine-tuning cover crop management and weather conditions are needed to benefit from such practice.

Keywords: early-interseeding, late-interseeding, annual ryegrass, crimson clover, forage radish, cereal rye, cover crop mixtures,

INTRODUCTION

The corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotation dominates agricultural production in the U.S. upper Midwest. This system is characterized by high external inputs, and an extended fallow period. During the fallow period, soils are vulnerable to erosion and essential plant nutrients can be lost to ground and surface waters. Integrating cover crops into the rotation can help to prevent those issues. Cover crops deliver multiple ecosystem services, including reduced nutrient losses (Hanrahan et al., 2018; Kladivko et al., 2014) through nutrient uptake (Ranells & Wagger, 1997), reduced soil erosion (Kaspar & Singer, 2011), enhanced soil fertility (Sullivan et al., 1991) and water dynamics (Basche et al., 2016), and weed suppression (Baraibar et al., 2018; Hayden et al., 2014). They are promoted as a best management practice to avoid water quality impairment (Lenhart, C., Gordon, B., Peterson, J., Eshenaur, W., Gifford, L., Wilson, B., Stamper, J., Krider, L. and Utt, 2017) and as a soil management tool (Kaspar & Singer, 2011), but their adoption remains low (Dunn et al., 2016). In northern climates, the period for cover crop establishment after corn harvest is limited by daylight hours and decreasing air temperature. However, interseeding into standing corn may enhance cover crop establishment and function.

Studies conducted in Minnesota report that cover crops interseeded at V7 corn reduce soil nitrate without reducing corn yield (Noland et al., 2018). The same authors report that inadequate cover crop termination resulted in reduced soil moisture content during a dry season that penalized soybean yield. Another study in Minnesota found that cereal rye aerially interseeded into corn or soybean in mid-August to mid-September produced more than 45 lb/ac (50 kg ha^{-1}) of biomass in 40% of the instances observed (Wilson et al., 2013). Those results evidence that interseeding cover crops is a practice in need of more information to help making informed decisions aiming their adoption by corn producers. For example, information on the performance of cover crops species is needed in the region. Until recently, research on cover crops in the U.S upper Midwest focused on a few species, CR being the most popular (CTIC, NCSARE, 2016). There is also work underway to identify alternative cover crops such as winter-hardy legumes like hairy vetch (*Vicia villosa* Roth) and emerging oilseed crops like field pennycress (*Thlaspi arvense* L.) and winter camelina [*Camelina sativa* (L.) Crantz], which could be used for double purpose in double-cropping (sequential- or relay-cropping) with corn or soybean; cash (Berti et al., 2017; Ott et al., 2019) or cover crops (Liu et al., 2019). This study aimed to increase the knowledge of cover crop interseeding into corn and soybean. The specific objectives of the study were to: 1) compare the establishment and growth of early- and late-interseeded cover crops across multiple environments, 2) evaluate the effect of late-interseeded CR on soil moisture at corn planting, and 3) assess the effect of interseeded cover crops on the productivity of corn.

Material and Methods

Treatments in this study were as follows:

The study was conducted at Lamberton and Waseca. Cover crops used in the trials were annual ryegrass [AR; *Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot], cereal rye (CR; *Secale cereale* L.), crimson clover (CC; *Trifolium incarnatum* L.), and radish (FR; *Raphanus sativus* L.). Treatments consisted on grasses as monocrops or mixed with the other cover crops to make two sets of four treatments each: ***set 1*** = AR, ARCC, ARCCFR, and NC (no cover as control); ***set 2*** = CR, CRCC, CRCCFR, and NC.

A thorough description of the procedures for this trial is provided in Chapter 1, Methods and Timeline section. This include description of locations, experimental design, management, data collection, and statistical analysis procedure. Methods not described in Chapter 1 are detailed under this section.

Results and Discussion

Weather Conditions

Weather during the study years was highly variable (Figure 9.1). Compared to the LTA, the 2016 – 2019 study period tended to be drier and warmer at Grand Rapids (Table 4.1), but wetter and cooler at Lamberton and Waseca (Table 2.1); 2016 was the wettest and warmest at all locations.

Table 4.1 Long-term average (LTA) of monthly rainfall totals and maximum (Tmax) and minimum (Tmin) air temperature at Grand Rapids. Experimental years are shown as departures from LTA.

Month	LTA (1990-2015)			Deviation from Long-Term Average (LTA) Weather Conditions											
				Rainfall (inches)				Maximum Temperature (F)				Minimum Temperature (F)			
	R (in)	Tmax (F)	Tmin (F)	2016	2017	2018	2019	2016	2017	2018	2019	2016	2017	2018	2019
Grand Rapids															
Jan	1.0	13	-2	0.0	0.0	-0.4	-0.7	7.2	-1.2	5.7	1.0	6.2	-3.1	-0.2	-4.2
Feb	0.9	18	2	0.2	0.2	-0.2	0.2	9.5	4.9	2.3	0.2	5.7	6.2	-6.9	-5.6
Mar	1.5	31	14	0.3	-0.2	-0.9	0.3	12.4	0.7	5.4	1.9	10.7	0.9	2.7	-2.8
Apr	2.2	48	29	-1.7	0.9	-1.3	0.1	2.5	3.2	-3.9	0.8	2.4	4.6	-8.6	1.1
May	3.6	63	43	-1.8	-1.3	0.2	-1.8	5.4	2.5	10.5	-2.7	0.0	7.3	2.8	-4.5
Jun	4.3	72	53	-0.7	0.2	0.4	1.7	1.0	2.1	2.7	1.6	-0.3	4.0	0.3	-2.3
Jul	3.5	77	58	-0.4	-1.9	-0.3	-1.1	1.8	-1.9	2.3	3.2	1.3	-0.8	0.3	-0.6
Aug	3.2	76	56	1.8	2.3	-1.8	-0.8	2.2	2.4	1.1	-1.7	1.1	1.9	-0.5	-7.6
Sep	2.8	66	48	2.4	2.7	0.4	1.8	2.5	-5.3	-1.1	0.3	3.7	-2.7	0.4	1.9
Oct	2.2	50	35	-1.3	-0.5	2.6	2.6	5.8	-3.6	-4.4	-0.9	4.5	-4.2	-3.4	-0.2
Nov	1.2	32	20	1.8	-0.6	-0.6	-0.7	14.9	-8.1	-4.5	-2.2	7.7	-7.9	-4.7	-1.3
Dec	1.1	18	5	1.0	-0.7	-0.9	-1.0	11.9	3.7	8.5	6.5	14.1	1.1	4.9	3.1
Year	**27.6**	**47**	**30**	**1.5**	**0.9**	**-2.8**	**0.7**	**6.4**	**-0.1**	**2.1**	**0.6**	**4.8**	**0.6**	**-1.1**	**-1.9**

Grand Rapids falls were wet, with rainfall ranging from 0.40 to 3 inches above the LTA, and maximum and minimum temperatures ranging from 7.7 and 5.2˚F above to -3.4 and -2.5˚F below the LTA, respectively. At Lamberton, the tendency towards wet and cool conditions was very clear, except for the 2016–2017 winter and 2018 spring, when rainfall was 1- and ¼-inch below the LTA, respectively. The 2018–2019 winter, with average maximum and minimum air temperatures 10˚F and 9˚F below the LTA, respectively, was by far the coldest season at Lamberton. At Waseca, a tendency towards wetter and cooler conditions were observed as well; except springs of 2016 – 2018 that were drier than the LTA spring conditions (Table 4.1).

CEREAL RYE HEAT UNITS

Cover crop GDD accumulation varied among locations and years. At Grand Rapids, the early-interseeded cover crops accumulated 1300-1400 GDDs from seeding to fall harvest, whereas at Lamberton and Waseca 400-500 GDDs more were accumulated. Similarly, the late-interseeded cover crops at Grand Rapids accumulated fewer GDD compared with Lamberton and Waseca. Interseeding cover crops approximately two-weeks earlier in fall 2018 resulted in an additional accumulation of GDD before fall frost at Grand Rapids, Lamberton, and Waseca, respectively (Table 4.2).

Table 4.2 Accumulated growing degree-days of early- and late-interseeded cereal rye cover crop at fall frost and before spring termination.

Location	**Period**	**Early-interseeded**			**Late-interseeded**		
		*Fall**	*Spring⁑*	*Full season*	*Fall*	*Spring*	*Full season*
Grand Rapids	2016-2017	-	-	-	-	-	-
	2017-2018	1375	217	1592	445	217	662
	2018-2019	1331	185	1516	627	187	814
	Average	*1353 (±31)*	*201 (±23)*	*1554 (±54)*	*536 (±129)*	*202 (±21)*	*738 (±107)*
Lamberton	2016-2017	1818	270	2088	528	277	805
	2017-2018	1824	210	2034	614	285	899
	2018-2019	1877	216	2093	725	296	1021
	Average	*1840 (±32)*	*232 (±33)*	*2088 (±33)*	*622 (±99)*	*286 (±10)*	*934 (±150)*
Waseca	2016-2017	-	-	-	605	217	822
	2017-2018	1870	268	2138	725	75	800
	2018-2019	1795	236	2031	762	248	1010
	Average	*1833 (±53)*	*252 (±23)*	*2085 (±76)*	*697 (±82)*	*180 (±92)*	*871 (±115)*

*From seeding to first frost day and ⁑ from first frost day to spring termination. Values followed by ± one standard deviation. Trial started in fall 2017 at Grand Rapids, and was lost due to flood the first year at Waseca.

SOIL MOISTURE AT CORN PLANTING

Compared with the no cover treatment, cover crops did not affect soil moisture at the time of corn planting, which occurred on the same day or up to 10 d after cover crop termination. Location, year and soil depth influenced soil moisture at corn planting at Grand Rapids, Lamberton, and Waseca (Figure 4.1). The 4-8 inches (10-20 cm) soil layer had less moisture than the 8-12 (20-30 cm) inches layer, except at corn planting at Grand Rapids in 2017 and Lamberton in 2018. Significant differences among all three soil layers occurred at Lamberton and Waseca in 2017 and at Grand Rapids in 2018.

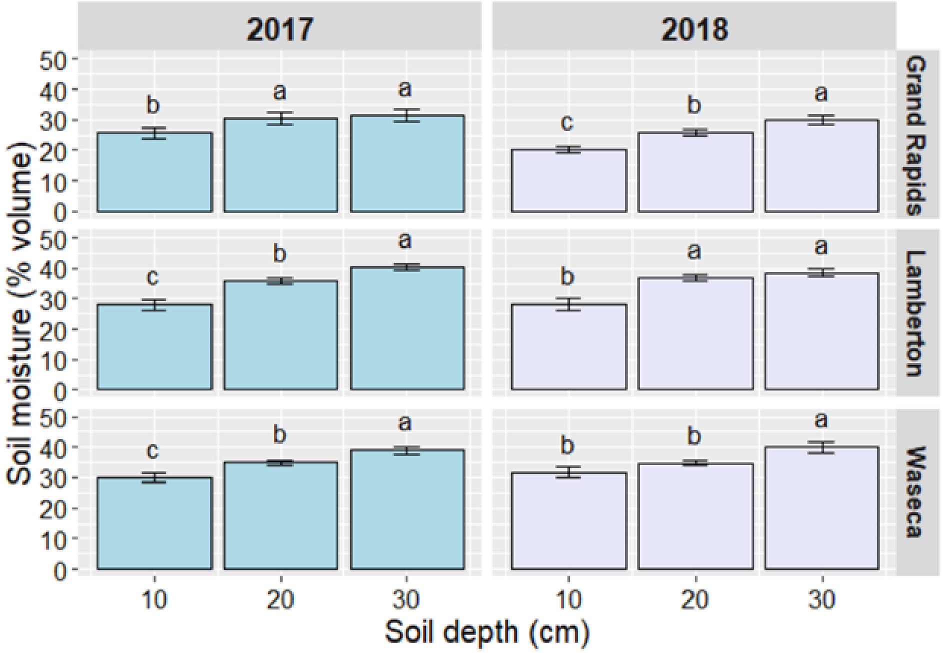


Figure 4.1. Mean soil moisture in the 0-4, 4-8, and 8-24 inch (0-10, 10-20, and 20-30 cm) soil layers at corn planting after CR cover crop termination in 2017 and 2018 at Grand Rapids, Lamberton, and Waseca. Within a year and location, different lowercase letters indicate significant differences (< 0.05) between means. Error bars are standard errors of the mean.

CANOPY COVER AND BIOMASS OF LATE-INTERSEEDED COVER CROPS

Canopy cover was significantly affected by location, year, and their interactions and by cover crops at fall frost. Cover crop strategy did not influence cover crop biomass, soil moisture at corn planting, or corn aboveground biomass and yield. Location and soil depth affected soil moisture at corn planting, and location, year, and their interaction (Table 4.3).

Table 4.3 Significance of fixed effects on fall canopy cover and biomass of late-interseeded cover crops, biomass and grain yield of corn following cover crops, and volumetric soil water content at corn planting.

Source of variation	**Fall frost**		**Spring termination**		**Corn biomass**	**Corn grain yield**	**VWC at corn planting**
	Canopy cover	*Biomass*	*Canopy cover*	*Biomass*			
Location (L)	<0.01	<0.01	<0.01	0.63	<0.01	<0.01	<0.01
Year (Y)	<0.01	<0.01	<0.01	<0.01	<0.01	0.03	0.01
Cover crop (C)	<0.01	<0.01	0.23	0.15	0.76	0.63	0.14
Soil depth (D)							<0.01
L×Y	<0.01	0.24	<0.01	0.26	<0.01	<0.01	<0.01
L×C	0.05	0.11	0.95	0.26	0.37	0.94	0.12
Y×C	0.79	0.68	0.27	0.24	0.26	0.97	0.87
L×D							<0.01
Y×D							0.97
C×D							0.52
L×Y×C	0.59	0.82	0.93	0.16	0.84	0.29	0.9
L×Y×D							0.01
L×C×D							0.49
Y×C×D							0.9
L×Y×C×D							0.33

At all locations and for all late-interseeded cover crop strategies, cover crop canopy cover in the fall was 35% or less in 2017 and 2018 (Figure 4.2; Figure 9.3). Cover crop canopy cover was greatest at Lamberton fall 2017, whereas in 2018 Waseca had the greatest; in both years, canopy cover was least at Grand Rapids.

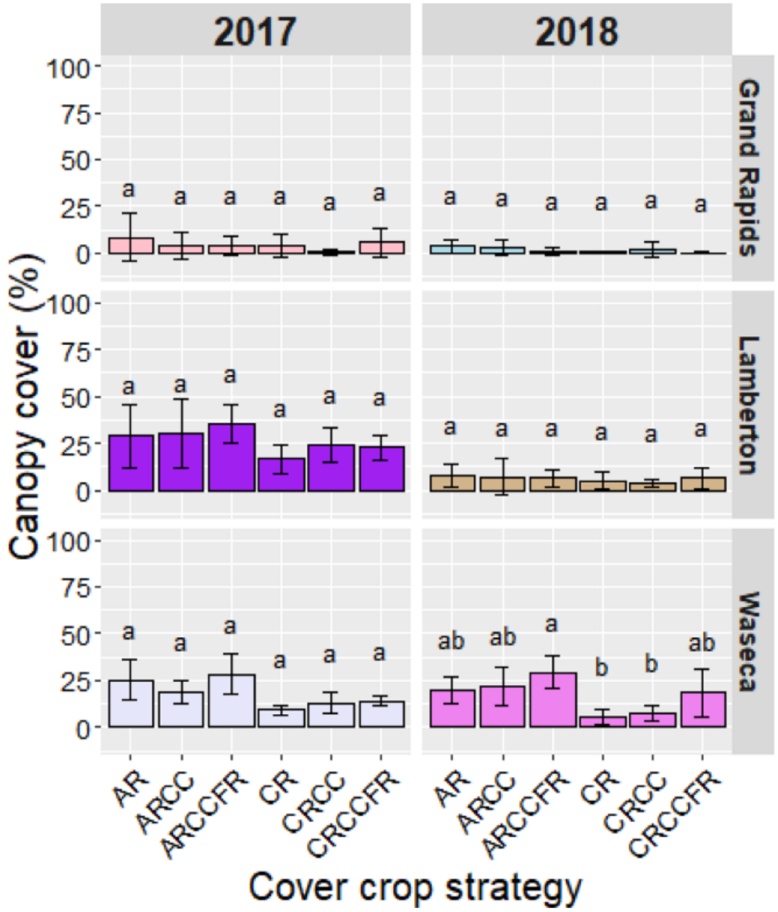


Figure 4.2 Canopy cover at fall frost of late-interseeded cover crops. For a given year within location, columns with different letters differ significantly at $P < 0.05$. Error bars are standard errors of the mean. AR = annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye.

The average cover crop biomass in the fall was marginal at all three locations. At Grand Rapids in 2017 was ~68 lb DM/ac (0.076 Mg DM ha^{-1}) and significantly less (9.0 lb DM/ac – 0.010 Mg DM ha^{-1}–) in 2018. At Lamberton, mean cover crop biomass in the fall was 133 and 68 lb DM/ac (0.149 and 0.076 Mg ha^{-1}) in 2017 and 2018, respectively. Waseca had the least year-to-year variation in cover crop biomass in the fall, with 141 and 120 lb DM/ac (0.158 and 0.134 Mg DM ha^{-1}) in 2017 and 2018, respectively (Table 4.4).

Table 4.4 Fall biomass of late-interseeded cover crops at three MN locations during two years.

Location	**Cover crop**[§]	**2017**	**2018**
		Biomass (kg ha^{-1})[¶]	
Grand Rapids	AR	0.21 ± 0.30	0.02 ± 0.02
	ARCC	0.07 ± 0.08	0.02 ± 0.02
	ARCCFR	0.08 ± 0.09	0.01 ± 0.01
	CR	0.03 ± 0.03	0.00 ± 0.00
	CRCC	0.00 ± 0.01	0.00 ± 0.00
	CRCCFR	0.06 ± 0.07	0.00 ± 0.00
	Average	*0.076 ± 0.132*	*0.010 ± 0.014*
Lamberton	AR	0.12 ± 0.03	0.08 ± 0.09
	ARCC	0.18 ± 0.10	0.08 ± 0.11
	ARCCFR	0.18 ± 0.07	0.09 ± 0.07
	CR	0.12 ± 0.06	0.06 ± 0.05
	CRCC	0.13 ± 0.07	0.05 ± 0.03
	CRCCFR	0.17 ± 0.09	0.10 ± 0.09
	Average	*0.149 ± 0.071*	*0.076 ± 0.070*
Waseca	AR	0.20 ± 0.09	0.12 ± 0.03
	ARCC	0.17 ± 0.08	0.16 ± 0.09
	ARCCFR	0.27 ± 0.10	0.22 ± 0.08
	CR	0.09 ± 0.03	0.05 ± 0.04
	CRCC	0.10 ± 0.03	0.10 ± 0.03
	CRCCFR	0.12 ± 0.05	0.16 ± 0.11
	Average	*0.158 ± 0.089*	*0.134 ± 0.085*

§ AR = annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye

¶ 1 kg ha^{-1} ≈ 0.90 lb/ac. Values are followed by ± one standard deviation

The direct consequence of poor fall growth was a poor spring growth at termination, which was marginal during the two years at all three locations (Table 4.5).

Table 4.5 Spring biomass of late-interseeded cover crops at three MN locations during two years.

Location	Cover crop§	2018	2019
		Biomass (kg ha^{-1})¶	
Grand Rapids	CR	0.28 ± 0.05	0.04 ± 0.06
	CRCC	0.26 ± 0.10	0.01 ± 0.01
	CRCCFR	0.49 ± 0.07	0.03 ± 0.03
	Average	*0.34 ± 0.13*	*0.03 ± 0.04*
Lamberton	CR	0.55 ± 0.25	0.01 ± 0.01
	CRCC	0.51 ± 0.20	0.01 ± 0.01
	CRCCFR	0.41 ± 0.16	0.01 ± 0.00
	Average	*0.49 ± 0.20*	*0.01 ± 0.01*
Waseca	CR	0.64 ± 0.35	0.03 ± 0.02
	CRCC	0.30 ± 0.13	0.03 ± 0.03
	CRCCFR	0.35 ± 0.18	0.01 ± 0.01
	Average	*0.43 ± 0.27*	*0.02 ± 0.02*

§ AR = annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye

¶ 1 kg ha^{-1} ≈ 0.90 lb/ac. Values are followed by ± one standard deviation

CANOPY COVER AND BIOMASS OF EARLY-INTERSEEDED COVER CROPS

Location, year, cover crop strategy, and their interactions influenced early-interseeded cover crop canopy cover and biomass in the fall. Corn biomass and yield were influenced by location, year, and the interaction of location and year (Table 4.6).

Table 4.6 Significance of fixed effects on fall canopy cover and biomass of early-interseeded cover crops and biomass and grain yield of corn.

Source of fixed variation†	Cover crop at fall frost		Corn	
	Cover crop canopy cover	Cover crop biomass	Biomass	Grain yield
Location (L)	<0.01	<0.01	<0.01	<0.01
Year (Y)	<0.01	<0.01	0.0334	<0.01
Cover crop strategy (C)	<0.01	<0.01	0.977	0.198
L x Y	<0.01	0.195	<0.01	<0.01
L x C	<0.01	<0.01	0.702	0.351
Y x C	<0.01	<0.01	0.542	0.726
L x Y x C	<0.01	<0.01	0.439	0.0960

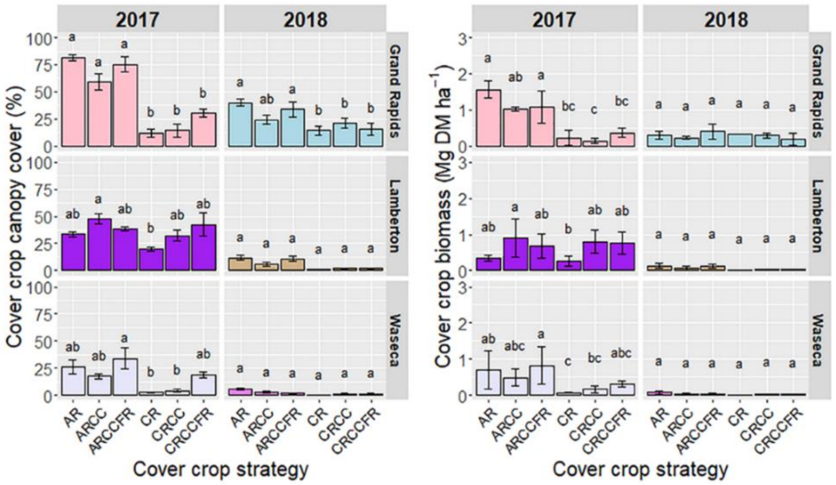


Figure 4.3 Early-interseeded cover crop canopy cover (left) and biomass (right) at fall frost. Different lowercase letters over bars indicate significant difference at $P < 0.05$. Vertical lines represent two standard errors.

Except for ARCC, AR-based strategies at Grand Rapids had more canopy cover than CR-based strategies in 2017 and 2018. Except for ARCC in 2017, all cover crop strategies produced similar canopy cover at Lamberton. Except for ARCCFR in 2017, all cover crop strategies produced similar canopy cover at Waseca. At all three locations cover crops performed better in 2017 than in 2018 (Figure 9.4). Early-interseeded cover crop biomass in the fall ranged from nothing for CR at Waseca in 2018 to as high as 1401 lb DM/ac (1.57 Mg DM ha^{-1}) of AR at Grand Rapids in 2017. At all three locations, AR-based strategies most frequently produced more biomass in fall of 2017 compared with CR-based strategies. No differences in fall biomass were observed between any cover crop strategy at any location in 2018 (Figure 4.3). Spring regrowth of CR from the early-interseeded study was low at all locations in 2018 and did not grow at Lamberton in spring 2019.

CORN BIOMASS- AND GRAIN-N

Corn biomass-N was significantly different among cover crop strategies in 2017 and 2018 at Lamberton and Waseca while no differences were observed at Grand Rapids. On the other hand, corn grain-N was significantly affected by cover crop strategies in 2017 at Grand Rapids only; the CR control accumulated the most N and AR accumulated the least N (Table 4.7). At Lamberton, mean separation test found no differences among cover crop treatments. Corn grain N accumulation across all cover crop strategies averaged 103 lb/ac (116 kg ha^{-1}) in 2017 and 114 lb/ac (128 kg ha^{-1}) in 2018. Data for 2017 corn grain was not available for Waseca due to inconsistencies; in 2018, however, no differences in corn grain-N were observed among cover crop treatments, which averaged 86 lb/ac (96 kg ha^{-1}).

Table 4.7 Corn biomass- and grain-N as affected by late-interseeded cover crops during two growing seasons at three Minnesota locations.

Cover crop[§]	**Grand Rapids**		**Lamberton**		**Waseca**	
	2017	**2018**	**2017**	**2018**	**2017**	**2018**
				Biomass-N (kg ha^{-1})[†]		
AR	76	80	58ab	120ab	57bcd	55ab
ARCC	90	108	59ab	115ab	52cd	45b
ARCCFR	84	116	79a	107ab	49cd	51ab
ARNC	84	121	62ab	96b	45d	66a
CR	78	117	66ab	102ab	89b	51ab
CRCC	77	103	77a	93b	99a	62ab
CRCCFR	84	107	52b	127ab	73bc	50ab
CRNC	90	108	48b	130a	87b	54ab
				Grain-N (kg ha^{-1})		
AR	78b	102	109	123	-	105
ARCC	87ab	97	105	121	-	96
ARCCFR	88ab	100	109	120	-	103
ARNC	84ab	95	113	124	-	99
CR	85ab	87	112	129	-	89
CRCC	93ab	100	134	135	-	87
CRCCFR	94ab	93	121	135	-	90
CRNC	96a	102	125	136	-	103

[§] Annual ryegrass, AR; Crimson clover, CC; Forage radish, FR; No cover, NC; Cereal rye, CR

[†] Within a location and year, mean values followed by a different lowercase letter are significantly different at $P < 0.05$. 1 kg ha^{-1} ≈ 0.90 lb/ac.

CORN BIOMASS AND YIELD

Corn biomass and grain yield from the late-interseeded cover crops study were both affected by location, year, and by their interaction, but were not by cover crop strategy (Table 4.3). Both biomass and grain yield were less in 2017 than in 2018 at Grand Rapids; less biomass and more yield in 2017 than in 2018 at Lamberton; and greater in 2017 than in 2018 at Waseca. For a given year within a locations, corn yield was not significantly different among treatments (Figure 4.4).

Similarly, biomass and grain yield of corn from the early-interseeded cover crops study were both affected by location, year, and their interaction, but no cover crop effect was observed. Overall, biomass yield was slightly higher at Grand Rapids, but grain yield tended to be similar (Table 4.8). Excess rain in Lamberton and Waseca.

Table 4.8 Biomass- and grain-yield of corn as affected by early-interseeded cover crops during two growing seasons at three Minnesota locations.

Location	**Cover Crop Strategy**[§]	**Biomass Yield (lb/ac)**		**Grain Yield (lb/ac)**	
		2017	*2018*	*2017*	*2018*
Grand Rapids	AR	23246 ± 1792	23284 ± 1943	10598 ± 891	10121 ± 446
	ARCC	22280 ± 2561	25148 ± 2171	10923 ± 270	9481 ± 511
	ARCCFR	24254 ± 3227	23942 ± 1041	10909 ± 539	9812 ± 445
	ARNC	24956 ± 1714	24798 ± 1690	10366 ± 186	9824 ± 791
	CR	23591 ± 2813	22936 ± 2970	9986 ± 815	10111 ± 444
	CRCC	24526 ± 1343	25282 ± 2488	10306 ± 223	10067 ± 538
	CRCCFR	23433 ± 1092	25880 ± 3009	10560 ± 77	10122 ± 540
	CRNC	24588 ± 1909	23966 ± 2303	10428 ± 635	9887 ± 832
	Average	*23859 ± 2056*	*24404 ± 2202*	10509 ± 454	9928 ± 568
Lamberton	AR	16942 ± 2558	20881 ± 1386	9492 ± 982	10063 ± 1237
	ARCC	18655 ± 2321	19244 ± 1457	9512 ± 1126	11255 ± 177
	ARCCFR	15493 ± 1843	19276 ± 2608	9488 ± 334	10779 ± 452
	ARNC	15720 ± 2455	19454 ± 855	8742 ± 1230	10461 ± 1045
	CR	16650 ± 2418	21263 ± 844	9656 ± 977	11027 ± 389
	CRCC	15479 ± 3687	21049 ± 2323	9889 ± 1123	10461 ± 652
	CRCCFR	15526 ± 3156	20647 ± 782	9433 ± 1224	11022 ± 380
	CRNC	15593 ± 2356	17670 ± 860	9430 ± 1325	10722 ± 996
	Average	*16257 ± 2599*	*19935 ± 1389*	9455 ± 1040	10724 ± 666
Waseca	AR	21577 ± 1302	20580 ± 6678	10467 ± 759	8616 ± 585
	ARCC	23942 ± 2035	19251 ± 4172	10452 ± 670	9036 ± 992
	ARCCFR	21423 ± 2138	22577 ± 3720	10199 ± 48	8754 ± 1035
	ARNC	22329 ± 3607	20505 ± 1515	10170 ± 620	8081 ± 673
	CR	21249 ± 3566	19934 ± 2981	10105 ± 612	7266 ± 936
	CRCC	22840 ± 3311	17201 ± 4408	10578 ± 693	7100 ± 749
	CRCCFR	21249 ± 1336	22019 ± 2834	10597 ± 301	8179 ± 1415
	CRNC	21881 ± 3887	20268 ± 3253	10646 ± 411	8539 ± 762
	Average	*22061 ± 2648*	*20292 ± 3695*	10402 ± 514	8196 ± 893

[§] AR = annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye, NC = no cover (control). Values are followed by± one standard deviation.

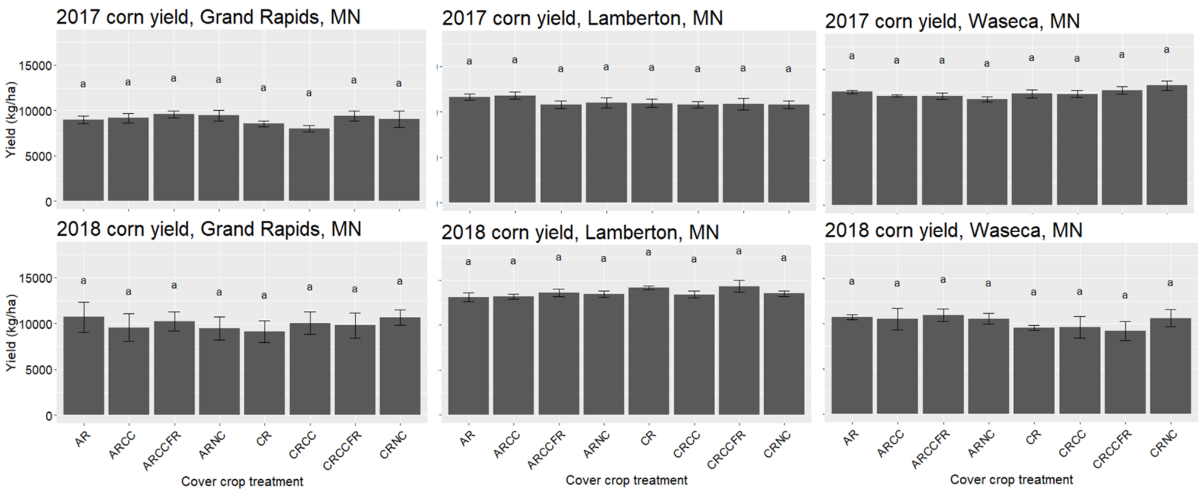


Figure 4.4 Grain yield of corn as affected by late-interseeded cover crops in 2017 and 2018 at Grand Rapids, Lamberton, and Waseca.

CONCLUSIONS

This study provides insights into the potential and effects of cover crops on corn productivity in the U.S. upper Midwest. It highlights the opportunity for broadcast interseeding cover crops at V4-V6 (early-interseeded) and R5-R6 (late-interseeded) corn.

Winterkilled cover crops, including early- and late-interseeded in the AR-based strategies, produced greater total cover crop canopy cover and biomass by fall frost than CR-based strategies. These findings suggest that AR may be an equally good or better option compared with CR in terms of producing canopy cover and biomass as a cover crop. However, AR-based strategies are all winterkilled, eliminating spring management before planting corn as well as the opportunity to provide environmental services in the springtime.

Increased GDD due to early planting of late-interseeded cover crops did not translate into greater cover crop establishment or more growth. Conversely, early-interseeded cover crops naturally accumulated more GDD thereby producing greater canopy cover and biomass than late-interseeded cover crops in most cases.

Our results show that interseeding cover crops into corn at V4-V6 corn produced highly variable results but was not detrimental to corn production. Regrowth of CR did not reduce soil moisture at corn planting or subsequent biomass- and grain-yield.

CHAPTER 5 – COVER CROPS AT MULTIPLE LOCATIONS: EFFECT OF COVER CROPS ON N DYNAMICS IN CORN PRODUCTION ACROSS MN

ABSTRACT

There is increasing pressure to improve nitrogen (N) use efficiency in corn (*Zea mays* L.) production systems. Recycling residual N with the use of cover crops represent one approach to improving efficiency. We monitored the fate of N in corn plots with early- and late-interseed cover crops at Grand Rapids, Lamberton, and Waseca. Cover crops used were annual ryegrass (AR; *Lolium multiflorum* L.) and cereal rye (CR; *Secale cereale* L.) as monocultures and in mixtures with crimson clover (CC; *Trifolium incarnatum* L.) and forage radish (FR; *Raphanus sativus* L.). We found that cover crops affected soil NO_3-N in well drained, somewhat poorly drained clay loam soils, but had no effect on a well-drained loam soil. Late-interseeded CR-based cover crops were effective in reducing NO_3-N in the soil solution at all 3-study locations; at Grand Rapids, however, those differences may have been due to coarse soils. NO_3-N in the soil solution was directly proportional to growth; i.e., marginal growth resulted in no NO_3-N reduction, mostly at Lamberton and Waseca. Highly variable cover crop biomass-N made it unclear to determine the strategy with the greatest potential for residual N use at all three locations. At Grand Rapids, the northernmost location, higher biomass-N was observed in early- than late-interseeded cover crops. This is likely due to the greater window opportunity for growth since cover crops were established at V4-V6 corn in the former and at R5-R6 in the latter. Annual ryegrass-based cover crops at Grand Rapids had more biomass-N than CR-based cover crops when early-interseeded, and biomass-N in AR monocrop was higher than in mixtures. Thus, early-interseeding AR at Grand Rapids may be the best option for improving the N use efficiency of corn cropping systems. At Lamberton and Waseca, early- and late-interseeded the 3-way mixtures of ARCCFR and CRCCFR had more biomass-N than monocultures and 2-species mixtures. However, results were not significantly different from other treatments. Early-interseeded cover crops did not affect corn biomass- and grain-N, a result that may encourage such a practice. In contrast, late-interseeded cover crops were associated with differences in corn biomass- and grain-N. Our results suggest early-interseeding cover crops to have the capacity to provide ecosystem services, but the high variability in results and the short duration of the project call for further research in such practice.

Keywords: sustainable corn, N dynamics, N fate, leaching, residual N

INTRODUCTION

Surface and groundwater contamination have been linked to the accumulation of excess N from agricultural runoff (David et al., 2010; Kladivko et al., 2014). Estimates attribute 52% of the N from agricultural sources contributing to the Gulf of Mexico Hypoxic Zone to corn and soybean [*Glycine max* (L.) Merr.] grown in the United States (Alexander et al., 2008). Consequently, there is mounting pressure to improve nitrogen (N) use efficiency in corn (*Zea mays* L.) production systems. Nitrogen, an essential nutrient for plant growth that is often limited in nature, is supplemented from synthetic sources in conventional production to meet the high requirement of corn. At the same time, corn has a limited N-fertilizer recovery efficiency estimated at 37% (Cassman & Walters, 2002), and residual N is vulnerable to loss through multiple pathways. While synthetic N fertilizer has resulted in an increase in agricultural productivity it has also been linked to a decline in water and air quality (Donner et al., 2004) and related social costs (Keeler et al., 2016). Abundant in the atmosphere, N must be converted from its inert form (N_2) to a plant-usable form such as ammonium (NH_4^+) or nitrate (NO_3^-). Residual $NO_3^- N$ is soluble in water and can be assimilated by plants through roots uptake (Rhezali & Lahlali, 2017) or lost via surface runoff, denitrification, and leaching. Additionally, field conditions (e.g., soil temperature and soil moisture) dictate application timing, which does not align necessarily with corn demand. Despite the challenges, opportunities to improve N use efficiency of corn cropping systems, while maintaining yield, are being pursued.

Cover crops extend the period of living green cover on the landscape, and are reported to improve NUE of corn (Kaye et al., 2019) by immobilizing residual N in their tissue, thereby reducing the soil N that might otherwise be lost (Hanrahan et al., 2018). Nutrients recycling (Ranells & Wagger, 1996), soil erosion reduction (Kaspar & Singer, 2011), and wildlife habitat (Wilcoxen et al., 2018) are among some of the benefits of cover crops. Excess N in the soil can be captured with cereal rye (*Secale cereale* L.; CR) cover crop, a well suited species for conditions in Minnesota due to its winter hardiness and capacity to emerge at air temperature as low as 4.4°C (Mirsky et al., 2009). As a result, CR is well studied and considered as an effective N scavenger capable of reducing N losses through drainage water (Feyereisen et al., 2006; Kaspar et al., 2012; Malone et al., 2014). It has been reported that CR has a stabilizing effect during extreme weather events (Basche et al., 2016; Daigh et al., 2014). However, uncertainties remain regarding the outcomes of CR on corn yield (Krueger et al., 2012; Marcillo & Miguez, 2017; S. Snapp & Surapur, 2018), allelopathic effects (Raimbault et al., 1990), seedling diseases (Acharya et al., 2016), and its economics (Roesch-McNally et al., 2018).

Several strategies have been suggested to address these concerns, including the use of winterkilled species to reduce management costs. Species from such a strategy provide fall ground cover while eliminating the need for springtime termination before planting corn. Other cover crop strategies include mixtures, yet experience remains limited in cool and wet regions (Kaye et al., 2019). Concerns about management time may be addressed by interseeding cover crops into corn. Reported interseeding experiences include aerial broadcasting CR into mature corn (Wilson et al., 2013), drilling monoculture and mixture cover crops at V2-V4 corn collar stages (Curran et al., 2018), and experimenting with different levels of soil disturbance at the V7 leaf collar stage (Noland et al., 2018). Drill interseeding cover crops at V2-V3 corn was found to reduce corn yield (Curran et al., 2018), while no yield reductions were observed at V4-V7 (Curran et al., 2018; Noland et al., 2018).

The present research sought to build on the existing knowledge of cover crop options for cool climates with rainfed agriculture. Specific objectives were to: 1) assess interseeded cover crops effects in soil NO_3-N, 2) evaluate the potential of cover crops to reduce NO_3-N in the soil solution, 3) determine cover crops N use, and 4) determine the effect of cover crops on biomass- and grain-N of corn. Field data was collected at three locations in the U.S. upper Midwest spanning a range of soil types and weather gradients.

MATERIAL AND METHODS

The general procedure for this trial was as described in Chapter 1, Methods and Timeline section. These include description of locations, experimental design, management, data collection, and statistical analysis. Procedures not described in Chapter 1 are detailed under this section.

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Weather conditions during the experimental years were as described under Chapter 4\Results and Discussion\Weather Conditions.

RESIDUAL SOIL NO_3-N

Results were highly variable at all locations; among cover crop treatments, no differences were observed at Grand Rapids, while significant differences were observed at Lamberton and Waseca (Table 5.1). At Grand Rapids, NO_3-N tended to be higher from monocrop cover crops in the soil profile in spring 2017; opposite tendency was observed for the same period in 2018. Cover crops did not influence soil NO_3-N at Grand Rapids, likely because of marginal growth. At Lamberton, differences on soil NO_3-N in the top 8 inches of soil were significant among cover crop strategies in spring 2017, being highest from ARCCFR and lowest form CR monocrop; no differences were observed in the 8-16 inches soil layer nor during the spring and fall of 2018. At Waseca, NO_3-N was significantly different among cover crop strategies in the 8-16 inches soil layer during the spring of both 2017 and 2018; the highest from the AR control and the lowest from the monocrop CR (Table 5.1).

Table 5.1 Residual soil NO_3-N (lb/ac) in the 0-8 and 8-16 inches soil layers from late-interseeded cover crop plots in spring and fall of 2017 and 2018.

Cover crop strategy	2017				2018			
	Spring		Fall		Spring		Fall	
	0-8 in	8-16 in	0-8 in	8-16 in	0-8 in	8-16 in	0-8 in	8-16 in
				Grand Rapids				
AR[§]	9.95	12.29	-	-	7.74	4.68	8.19	7.28
ARCC	7.43	11.61	-	-	11.87	8.84	6.43	8.24
ARCCFR	7.51	12.48	-	-	12.40	4.85	6.13	10.60
ARNC	8.81	13.60	-	-	21.29	16.55	5.66	7.63
CR	12.09	9.88	-	-	14.40	5.11	5.36	8.84
CRCC	10.80	12.30	-	-	13.63	10.23	6.21	8.49
CRCCFR	8.57	8.24	-	-	9.72	11.87	6.51	8.15
CRNC	8.96	13.26	-	-	12.87	5.37	6.89	8.40
				Lamberton				
AR	13.60ab	7.32	4.83ab	4.83ab	6.20	5.85	7.24	3.24
ARCC	14.01a	6.35	3.45b	3.66ab	7.52	6.48	8.57	3.59
ARCCFR	15.05a	5.94	4.83ab	2.76b	6.48	6.60	9.53	3.65
ARNC	13.52ab	7.93	6.55ab	4.34ab	7.06	7.24	10.68	3.59
CR	7.73b	3.52	7.18ab	4.56ab	5.62	6.89	9.53	4.51
CRCC	7.32b	4.34	9.26ab	7.10a	7.75	6.25	10.68	4.23
CRCCFR	9.59ab	4.69	7.66ab	4.76ab	5.09	6.37	9.88	4.28
CRNC	13.73a	7.73	10.24a	9.88a	5.97	5.32	8.99	3.82
				Waseca				
AR	6.31	6.89ab	-	-	3.19	6.67ab	9.74	9.87
ARCC	7.29	6.02ab	-	-	3.78	6.35ab	9.79	9.55
ARCCFR	6.78	6.60ab	-	-	4.26	6.09ab	9.86	10.96
ARNC	5.73	9.97a	-	-	3.97	7.82a	11.84	12.50
CR	4.98	4.34b	-	-	3.13	5.25c	12.74	11.92
CRCC	5.73	5.85ab	-	-	3.13	5.45bc	12.32	10.51
CRCCFR	7.24	7.58ab	-	-	3.78	8.14a	12.44	15.19
CRNC	7.64	6.02ab	-	-	4.33	7.50ab	13.16	14.36

[§] AR = Annual ryegrass, CC = crimson clover, FR = forage radish, NC = no cover crop (control), and CR = cereal rye

[‡] Within a location and year, values followed by a different lowercase letter are significantly different at P<0.05.

At all locations and within a soil depth, soil NO_3-N was not affected by early-interseeded cover crops. The dramatic increase observed in the soil profile at Waseca from spring to fall 2018 was most likely due to experimental errors we could not identify (Table 5.2).

Table 5.2 Residual soil NO_3-N (lb/ac) in the 0-8 and 8-16 inches soil layers from early-interseeded cover crop plots. Values are followed by ± one standard deviation.

Location	2017		2018			
	Fall		Spring		Fall	
	0-8 in	8-16 in	0-8 in	8-16 in	0-8 in	8-16 in
Grand Rapids	-	-	10.67 ± 5.18	9.68 ± 9.24	9.23 ± 2.24	8.71 ± 3.34
Lamberton	7.60 ± 3.60	3.49 ± 1.53	11.60 ± 4.00	5.11 ± 1.82	8.17 ± 2.57	9.22 ± 3.32
Waseca	5.95 ± 2.82	5.54 ± 2.72	7.19 ± 2.46	8.98 ± 8.98	30.32 ± 18.08	34.49 ± 25.87

NO_3-N IN SOIL SOLUTION

Seasonal NO_3-N concentration in the soil solution was collected only in the CR-based strategies. Although highly variable, cover crops tend to reduce NO_3-N in the leachate (Figure 9.2; Figure 9.6). Results showed that NO_3-N concentration in the soil solution was affected by location, year, cover crop strategy and their interactions (Table 5.3).

Table 5.3 Significance of fixed effects for NO_3-N in soil solution in response to six cover crop strategies late-interseeded into maize at Grand Rapids, Lamberton, and Waseca, MN in 2016, 2017, and 2018.

Source of variation§	**Spring**	**Summer**	**Fall**
Year (Y)	<0.01	0.08	<0.01
Location (L)	<0.01	<0.01	<0.01
Cover Crop Strategy (C)	<0.01	<0.01	<0.01
Y x L	<0.01	<0.01	<0.01
Y x C	<0.01	<0.01	<0.01
L x C	<0.01	<0.01	0.6
Y x L x C	<0.01	<0.01	<0.01

At Grand Rapids in fall 2017, NO_3-N concentration in soil solution was higher in CR than CRCC plots, whereas in fall 2018, NC had the highest and CR and CRCC the lowest NO_3-N concentration (Table 5.4). Year-to-year variation was only significant at Grand Rapids in the fall. At Lamberton, NO_3-N was significantly higher in the NC than in the cover crop treatments in spring and summer 2017; across years, the concentration of NO_3-N was lower in 2017. At Waseca, significantly lower NO_3-N concentration was observed in CR plots as compared to the NC treatment in spring 2017; lower levels were observed in summer and fall of 2018 as compared to 2016 and 2017.

Table 5.4 Effect of cover crops on NO_3-N (mg L^{-1}) in the soil solution at 40-inch depth in spring, summer, and fall.

Strategy[§]	**Grand Rapids**			**Lamberton**			**Waseca**		
	2016	**2017**	**2018**	**2016**	**2017**	**2018**	**2016**	**2017**	**2018**
Spring (March – May)									
CR	-	10.5±6.4	8.2±4.1	-	1.8bB	5.3A	-	1.5bB	5.4A
CRCC	-	5.5±1.6	8.0±4.5	-	3.2bB	6.9A	-	2.4abA	4.0A
CRCCFR	-	14.8±4.6	8.8±4.3	-	2.1bB	6.5A	-	2.8abA	4.8A
NC	-	12.7±4.1	12.4±8.2	-	8.9aA	7.1A	-	3.6aA	3.9A
Summer (June – August)									
CR	-	10.6±3.9	9.8 ±8.6	-	3.7bB	10.2A	-	3.7A	4.2A
CRCC	-	6.6±3.8	9.8 ±6.5	-	7.1bA	11.0A	-	4.2A	3.9A
CRCCFR	-	9.4±5.2	11.8 ±7.7	-	3.3bB	10.3A	-	5.3A	3.0B
NC	-	9.3±4.1	15.9 ±12.1	-	16.8a	11.5A	-	6.3A	3.2B
Fall (September – November)									
CR	10.1aB	10.9aA	13.4bA	7.9A	0.6B	6.0A	1.7AB	2.1A	0.3B
CRCC	12.9aA	5.6bB	9.4bAB	8.9A	0.4B	5.5A	0.9AB	1.7A	0.1B
CRCCFR	12.2aA	9.5abA	13.9abA	6.3A	1.3B	8.7A	1.6AB	3.2A	0.3B
NC	13.6aAB	7.9abB	23.1aA	7.4A	2.5B	9.4A	1.8AB	3.7A	0.7B

[§] CR = cereal rye, CC = crimson clover, FR = forage radish, and NC = no cover (control)

[†] Within a season and a given cover crop strategy, values followed by different uppercase letters are significantly different between years at $P < 0.05$.

[‡] Within a season, values followed by a different lowercase letter in a column are significantly different at $P<0.05$

BIOMASS-N OF COVER CROPS

Fall biomass-N of late-interseeded cover crop was low at all location-years; about 5 lb/ac (5.56 kg ha^{-1}) of AR at Grand Rapids in 2017, 16.15 lb/ac (18.15 kg ha^{-1}) from the 3-way CRCCFR mixture at Lamberton in 2017, and 10 lb/ac () from the 3-way ARCCFR mixture at Waseca in 2018 (Table 5.5).

Table 5.5 Fall biomass-N (kg N ha^{-1}) of late-interseeded cover crops at three locations in Minnesota.

Location	Cover crop[§]	2017	2018
Grand Rapids	*AR*	5.56 ± 4.51	0.64
	ARCC	2.25 ± 0.88	1.37
	ARCCFR	0.95 ± 0.44	0.21
	CR	1.14 ± 0.57	0.23
	CRCC	0.34	-
	CRCCFR	3.35 ± 0.54	-
Lamberton	*AR*	4.68b ± 1.38	3.79 ± 4.49
	ARCC	10.66ab ± 4.88	3.17 ± 4.20
	ARCCFR	16.11a ± 5.61	4.11 ± 3.09
	CR	4.65b ± 2.23	2.80 ± 2.16
	CRCC	9.05ab ± 3.96	2.07 ± 1.30
	CRCCFR	18.15a ± 9.6	4.76 ± 4.32
Waseca	*AR*	-	4.37b
	ARCC	-	5.63b
	ARCCFR	-	11.13a
	CR	-	2.78bc
	CRCC	-	2.57c
	CRCCFR	-	5.61bc

[§] Annual ryegrass, AR; Crimson clover, CC; Forage radish, FR; Cereal rye, CR [†]. Within a location and a year, values with the same lowercase letter are significantly different at P ≤ 0.05.

Biomass-N in early-interseeded cover crops at fall frost was significantly different among treatments, except for 2018 at Grand Rapids and Waseca (Figure 5.1). In fall 2017 at Grand Rapids, AR accumulated significantly more N than all other cover crop treatments except ARCC. At Lamberton in 2017, ARCCFR and CRCCFR accumulated more N than did monocultures, and in 2018, ARCCFR accumulated more N than all other cover crop treatments except for AR. At Waseca in 2017, ARCCFR accumulated significantly more N than CR and CRCC. Early-interseeded cover crop N accumulation at fall frost in 2018 did not exceed 2.33 kg ha^{-1}.

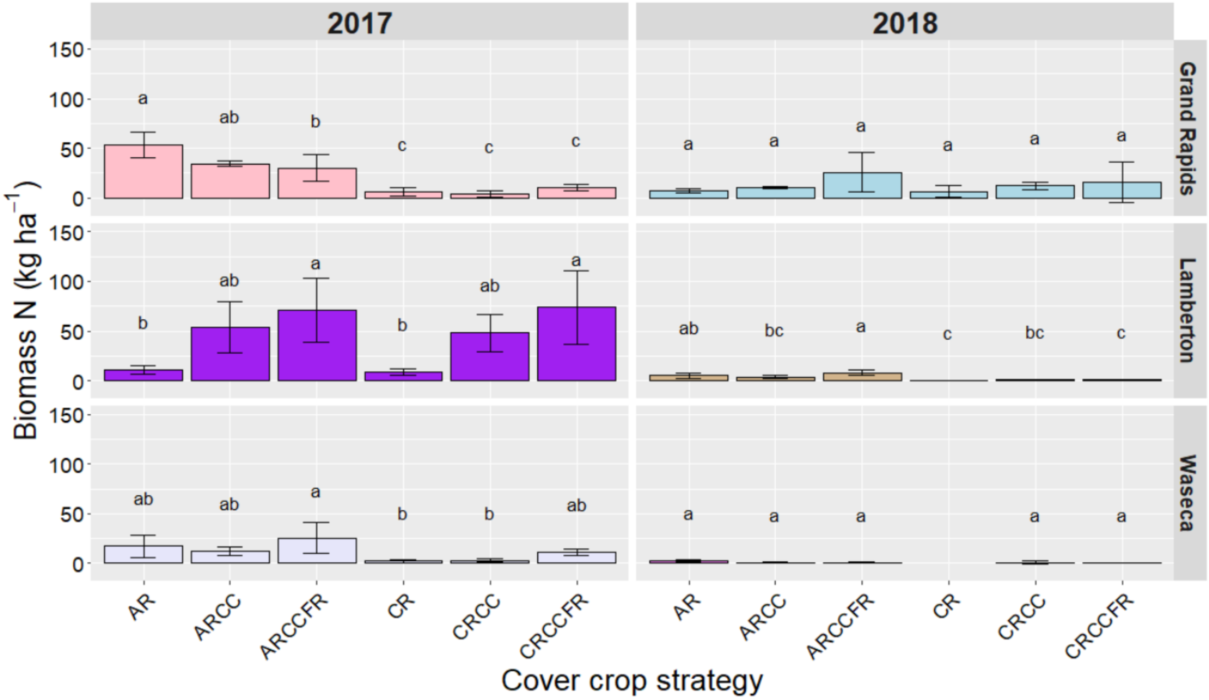


Figure 5.1 Biomass-N of early-interseeded cover crop at fall frost. Within a location and year, means with different lowercase letters indicate significant difference at *P*<0.05. Bars are standard errors of the mean.

BIOMASS- AND GRAIN-N OF CORN

Biomass-N of corn was not affected by late-interseeded cover crops at Grand Rapids, but significant differences were observed at Lamberton and Waseca in 2017 and 2018. At Lamberton in 2017, the biomass-N in the 3-way mixture of ARCCFR was higher than CRCCFR; in 2018, however, more biomass-N was observed in the CRNC than the other treatments. At Waseca, biomass-N from the 2-way mixture of CRCC was higher than all other treatments (Table 5.6).

Table 5.6 Biomass- and grain-N in corn following late-interseeded cover crops at three locations in Minnesota.

Cover crop[§]	Grand Rapids		Lamberton		Waseca	
	2017	2018	2017	2018	2017	2018
			Biomass-N (lb/ac)			
AR	67.7	71.2	51.6ab	106.8ab	50.7bcd	49.0ab
ARCC	80.1	96.2	52.5ab	102.4ab	46.3cd	40.1b
ARCCFR	74.8	103.3	70.3a	95.3ab	43.6cd	45.4ab
ARNC	74.8	107.7	55.2ab	85.5b	40.1d	58.8a
CR	69.4	104.2	58.8ab	90.8ab	79.2b	45.4ab
CRCC	68.6	91.7	68.6a	82.8b	88.1a	55.2ab
CRCCFR	74.8	95.3	46.3b	113.1ab	65.0bc	44.5ab
CRNC	80.1	96.2	42.7b	115.7a	77.5b	48.1ab
			Grain-N (lb/ac)			
AR	69.4b	90.8	109	109.5	-	93.5
ARCC	77.5ab	86.4	105	107.7	-	85.5
ARCCFR	78.3ab	89.0	109	106.8	-	91.7
ARNC	74.8ab	84.6	113	110.4	-	88.1
CR	75.7ab	77.5	112	114.9	-	79.2
CRCC	82.8ab	89.0	134	120.2	-	77.5
CRCCFR	83.7ab	82.8	121	120.2	-	80.1
CRNC	85.5a	90.8	111.3	121.1	-	91.7

[§] Annual ryegrass, AR; Crimson clover, CC; Forage radish, FR; No cover, NC; Cereal rye, CR

[†] Within a location and year, mean values followed by a different lowercase letter are significantly different at $P < 0.05$.

Both, corn biomass- and grain-N from early-interseeded cover crops were not influenced (Table 5.7). Year-to-year variation was observed in biomass-N at Lamberton, with a tripling amount from 2017 to 2018; similarly, corn grain-N in 2018 was nearly twice of that in 2017.

Table 5.7 Biomass- and grain-N of corn from early-interseeded cover crop plots at three locations in MN.

Location	**2017**		**2018**	
	Biomass	*Grain*	*Biomass*	*Grain*
		N (lb/ac)		
Grand Rapids	91	120	91	133
Lamberton	41	83	133	150
Waseca	-	98	58	101

RESIDUAL SOIL NO_3-N

Significant differences in residual soil NO_3-N among late-interseeded cover crop treatments were observed at Lamberton and Waseca. In spring 2017 at Lamberton in the 0-20 cm soil layer, less NO3-N was found in CR than ARCC and ARCCFR - which did not have any spring cover crop growth - and CRNC. In fall 2017 in the 0-20 cm soil layer, ARCC had lower residual soil NO3-N levels than CRNC, and in the 20-40 cm soil layer ARCCFR had lower levels than CRCC and CRNC. At Waseca in spring 2017, residual soil NO3-N in the 20-40 cm was reduced in CR compared with ARNC. Similarly, in spring 2018 in the 20-40 cm soil layer lower soil NO3-N levels were observed in CR and CRCC than in ARNC and CRCCFR. In spring 2018, CR had significantly less soil NO3-N than all other treatments, except CRCC. Cover crops did not influence residual soil NO3-N at Grand Rapids, likely because of marginal growth.

COVER CROP N ACCUMULATION

Nitrogen accumulation in cover crop biomass at the time of fall sampling was less than 20 kg ha-1 in 2017 and 2018 at all locations. Cover crop N accumulation at Grand Rapids was marginal both years, mainly because of little to no biomass either year. Averaged across treatments, cover crops at Grand Rapids accumulated 2.62 kg ha-1 in 2017 and 0.61 kg ha-1 in 2018. The greatest average cover crop N accumulation was observed in fall of 2017 at Lamberton (CRCCFR 18.15 kg ha-1). In 2018, however, cover crop N accumulation at Lamberton did not exceed 4.76 kg ha-1 (CRCCFR). Both CRCCFR and ARCCFR accumulated more N at Lamberton both years, though in 2018 N accumulation was similar among cover crop treatments. At Waseca, cover crop biomass N accumulation data was unavailable for analysis in fall 2017 due to misplaced samples nor in fall of 2018 due to poor cover crop establishment, limiting the collection of cover crops biomass and thus, N use was not determined. The ARCCFR treatment accumulated more N than other treatments in fall 2018 at Waseca. The N accumulation of late-interseeded CR-based cover crops was not affected by spring termination, before planting corn. At Grand Rapids in spring 2017, no differences among cover crop treatments were observed. Averaged across treatments, cover crop N accumulation at Grand Rapids in 2017 was 14.19 kg ha-1. No data was available for analysis of cover crop N accumulation for spring 2018 at Grand Rapids or spring 2017 at Lamberton due to lost samples. In spring 2018 at Lamberton, no differences in the N accumulation of late-interseeded cover crops at spring termination were observed; the pooled average of N accumulated among cover crops was rather marginal (0.54 kg ha^{-1}). Similarly, no differences in cover crops N accumulation were observed at Waseca in 2017 or 2018. With an average of 17.92 kg ha-1 across all treatments in 2017, CR-based cover crops accumulated more N; however, this amount was reduced to 2.70 kg ha-1 in spring 2018 (Table 5.8).

Table 5.8 Mean N content (Kg N ha^{-1}) in cover crop biomass at fall frost collection. Values following ± are the standard deviation of the mean.

Location	Cover crop strategy[§]	2017	2018
Grand Rapids	AR	5.56	0.64
	ARCC	2.25	1.37
	ARCCFR	0.95	0.21
	CR	1.14	0.23
	CRCC	0.34	-
	CRCCFR	3.35	-
Lamberton	AR	4.68b	3.79
	ARCC	10.66ab	3.17
	ARCCFR	16.11a	4.11
	CR	4.65b	2.8
	CRCC	9.05ab	2.07
	CRCCFR	18.15a	4.76
Waseca	AR	-	4.37b
	ARCC	-	5.63b
	ARCCFR	-	11.13a
	CR	-	2.78bc
	CRCC	-	2.57c
	CRCCFR	-	5.61bc

[§] Annual ryegrass, AR; Crimson clover, CC; Forage radish, FR; Cereal rye, CR

[†] Within a location and a year, mean values with the same lowercase letter are not significantly different at P<0.05.

CONCLUSIONS

Variability existed in the effect of fall- and early-interseed cover crops on NO_3-N in the soil and soil solution, as well as in N accumulation by cover crops across three U.S. upper Midwest locations included in this study. Evidence of the ability of cover crops to reduce the potential for N losses was observed, suggesting that cover crops may be a tool to improve N management in corn cropping systems. Interseeded cover crops had no effect on soil NO_3-N in a well-drained loam soil but were found to reduce soil NO_3-N relative to no cover in both the 0-20 cm and 20-40 cm layers on moderately well drained and somewhat poorly drained clay loam soils. Cereal rye-based late-interseeded covers were effective in reducing NO_3-N in the soil solution at all three study locations. However, at Grand Rapids differences in NO_3-N concentrations may be due to coarse soils and thresholds of cover crop growth exist at Lamberton and Waseca below which cover crops do not reduce NO_3-N concentrations in soil solution.

Highly variable cover crop N accumulation results make it unclear which cover crop treatments pose the greatest potential for each location. At Grand Rapids, the northernmost location, greater N accumulation occurred in early-interseeded cover crops than in late-interseeded. This is likely due to the greater number of GDD available to cover crops established at V4-V6 corn as compared with R5-R6. Annual ryegrass-based cover crops at Grand Rapids accumulated more N than CR-based cover crops when interseeded at V4-V6, and AR accumulated more than mixtures. Thus, deriving from the results of this study, interseeding AR into V4-V6 corn at Grand Rapids may be the best option for improving the N use efficiency of corn cropping systems. At Lamberton and Waseca, early- and late-interseeded ARCCFR and CRCCFR accumulated more N than monocultures and 2-sprecies mixtures of cover crops. However, they did not always accumulate significantly more N than other treatments and when differences did arise they were inconsistent making it challenging to derive any clear trends from the data.

Early-interseeded cover crops did not affect mature corn biomass and grain N content. This may encourage additional experimentation with V4-V6 interseeding. Late-interseeded cover crops, however, were associated with differences in corn biomass N corn grain N.

Given the high variability reported here and the short duration of the project, more research is needed to adequately address the questions posed here. To ensure greater cover crop success, future work could examine increasing the seeding rate and drill-interseeding cover crops. We conclude that interseeding could occur at V4-V6 leaf collar stage to enhance the capacity of cover crops to provide N loss reduction services to the corn cropping system.

CHAPTER 6 – COVER CROPS AT MULTIPLE LOCATIONS: WATER USE OF CROPS AND COVER CROPS

ABSTRACT

Diversification with cover crops is an alternative for the sustainable intensification of rainfed crop production systems, but competition for resources use may put at risk the productivity of primary crops. A study was conducted to i) determine the effect of late-interseeded cover crops in soil moisture and yield of subsequent crops, ii) quantify the water use (WU) and water use efficiency (WUE) of corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] from diversified cropping practices, and iii) quantify the WU and WUE of cover crops in corn and soybean rotation practices. The study was conducted from fall 2016 to spring 2019 at three location in the U.S. upper Midwest. Cover crop strategies included monoculture cereal rye (*Secale cereale* L.), 2-species mix of CR + crimson clover (Trifolium incarnatum L.), 3-species mix of CR + crimson clover + forage radish (Raphanus sativus L.); and a no cover crop control. Year and cover crop strategy did not affect soil water content nor yield of corn and soybean. Additionally, the increased number of cover crop species did not affect WU of the following primary crops. Averaged over six location-years, the WU for corn and soybean was 353 mm and 346 mm, respectively. Water use of cover crops during either fall or spring was not affected by the cover crop strategy; approximately 70% of the total evapotranspiration was due to evaporation. Averaged over six location-years, WUE for corn and soybean was 3.07 kg m^{-3} and 1.03 kg m^{-3}, respectively. The WUE of cover crops was highly affected by locations and year, and varied from as much as 1.58 kg m^{-3} to as little as 0.01 kg m^{-3}. Our findings may represent much of the U.S. upper Midwest conditions, as well as regions with similar climate and cropping practices.

Keywords. Evapotranspiration, cover crops, corn, northern locations, water productivity.

INTRODUCTION

Sustainable intensification through crop diversification aims to adopt practices that promote the use of inputs within the agroecosystem while maintaining or improving crop productivity. The average 2015-2019 production of corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] in the upper Midwest U.S. represented, respectively, 42 and 38% of the country's total; more than half of which from the Corn Belt (Green et al., 2018). The traditional 2-yr corn-soybean rotation is the most common cropping system in the region (Garciay Garcia & Strock, 2018; Grassini et al., 2015a). Such practice has shown to increase yield of both crops, but is criticized due to diversity loss, nitrogen pollution, and soil degradation (Grassini et al., 2015b; Mitsch et al., 2001; Syswerda et al., 2012). Sustainable intensification through diversification is reported as a strategy to improve productivity, stability, and profitability while reducing the environmental footprint of agroecosystems(Gaudin et al., 2015; Peltonen-Sainio & Jauhiainen, 2019). Diversifying cropping systems, however, must consider differences on resources use that may exist from one region to another.

Cover crops have received special attention as a viable option to diversify corn-soybean production systems in the region. Cover crops maintain or increase crop yield while reducing soil erosion, water runoff, and external inputs, improve soil physical properties and water quality and increase soil organic matter (Holderbaum et al., 1990). Cover crops reduce evaporation; hence increase water availability in the root zone (Unger & Vigil, 1998). Those benefits are affected by species, location, seeding time, growth length, timing of termination, and use (Campbell et al., 1984; Rusch et al., 2020). In addition, cover crops may affect soil water relations far into the next crop, much so that the practice might be better suited to humid and sub humid regions than to semiarid regions (Unger & Vigil, 1998). Available soil water is of major importance in rainfed agroecosystems like most corn and soybean in the U.S. Corn Belt. In the region, water is usually not a limiting factor to productivity (Horowitz et al., 2010; Hussain et al., 2019), but in some years limited soil water has been reported to reduce crop production (Suyker & Verma, 2009).

Because of the short growing season in the U.S. upper Midwest, winter cover crops are often the option to diversify corn and soybean production systems. Winter cover crops are seeded early or late in the growing season either as monocrops or mixed with winterkilled species, and terminated before or soon after planting the next primary crop the following spring (Rusch et al., 2020). For example, cereal rye (CR; *Secale cereale* L.), crimson clover (CC; *Trifolium incarnatum* L.), and forage radish (FR; *Raphanus sativus* L.) are reported as the most common cover crops in U.S., either as monocrop or mixed (CTIC, 2017). A study conducted in central Iowa, U.S. reports that CR increased soil water storage in a corn-soybean rotation (Courault & Ruget, 2001; Qi et al., 2011). For conditions in the coastal plain ecoregion of Maryland, U.S., Chen & Weil (2011) found that FR benefited corn root penetration in compacted soils while CR improved the availability of surface soil water. While less in known about CC, some evidences indicate available soil water to be a concern with its use (Meyer et al., 2018). A study by (Rusch et al., 2020) report that CR monocrop and mixed with CC and CCFR did not affect available soil water at corn planting for conditions in the upper Midwest U.S. While there is a legitimate concern that cover crops may reduce available soil water for the next cash crop in semi-arid regions, little is known about the effect of cover crops in soil water and its impact to subsequent crops in humid regions like the upper Midwest U.S.

Water is a limiting factor in rainfed crop production systems, and more so in water-limited environments (Jerry L. Hatfield & Dold, 2019). The intensification through diversification of rainfed cropping systems is reported to positively affect the water use efficiency of crops in tropical (Rockström, 2003) and semi-arid (Franco et al., 2018) regions. In water-abundant regions like the U.S. upper Midwest, however, such studies are limited. In the region, rainfall during the growing season is usually around 75% of the yearly total, which is sufficient to fulfill the water required by crops (Garciay Garcia & Strock, 2018). Such scenario could be an issue with intensification through diversification since higher use of resources is expected.

The objectives of this study were to i) determine the effect of late-interseeded cover crops in soil moisture and yield of subsequent crops, ii) quantify the water use (WU) and water use efficiency (WUE) of corn and soybean from diversified cropping practices, and iii) quantify the WU and WUE of cover crops in corn-soybean rotation practices. Our results provide insights on the potential effects of late-interseeded cover crops in corn and soybean rotation practices in a northern climate.

MATERIAL AND METHODS

The general procedure for this trial was as described in Chapter 1, Methods and Timeline section. These include description of locations, experimental design, management, data collection, and statistical analysis. Specific procedures to this study not described in Chapter 1 are detailed under this section.

DATA COLLECTION

SOIL WATER CONTENT MEASUREMENTS

Soil moisture was measured every 7-10 d at depths of 4, 8, 12, 16, 24, 40 inch (10, 20, 30, 40, 60, and 100 cm) using a PR2 profile probe (Delta-T Devices Ltd., Cambridge, UK). Only readings in the top 16 inches (40 cm) were used because deeper soil moisture readings showed little to no change (almost flat). The PR2 probe, a polycarbonate rod with electronic sensors at fixed intervals along its length, uses electromagnetic signals to measure the permittivity of the soil, which is then converted into volumetric soil water content (Delta-T Devices Ltd., Cambridge, UK). We monitored soil moisture in each plot from September 2016 to May 2019; the average of three measurements per depth was used.

PRODUCTIVITY OF CROPS AND COVER CROPS

Grain yield of corn and soybean and biomass yield of cover crops was obtained and processed as described by Rusch et al. (2020).

WATER USE AND WATER USE EFFICIENCY OF CROPS AND COVER CROPS

Water use or evapotranspiration of crops (*ETc*), including corn, soybean, and cover crops, was obtained from two methods: i) simplified field water balance (*ETc-wb*; eq. 3-4) and ii) weather-based x crop coefficient (*Kc*) approach (Allen et al., 1998) (eq. 5-6).

$$ET_{c-wb} = P_e \pm \Delta S \tag{Equation 3}$$

$$P_e = P_{total} \times (125 - 0.2P_{total})/12$$

$$\Delta S = \left(\overline{\theta}_{t2} - \overline{\theta}_{t1}\right)z$$

$$ET_{c-wb} = [P_{total} \times (125 - 0.2P_{total})/12] \pm \left(\overline{\theta}_{t2} - \overline{\theta}_{t1}\right)z \tag{Equation 4}$$

where

P_e = effective precipitation, ΔS = water storage in the active root zone in the time interval (*t2 – t1*) and depth *z*, P_{total} is the observed total monthly precipitation (mm) for $P_{total} < 250\ mm$, $\overline{\theta}$ = average moisture content in the top 16 inches of soil calculated from PR2 readings. The P_e was estimated in accordance with the USDA-Soil Conservation Service method (M. Smith, 1992). Simplifications to our water balance included irrigation (*I*) = 0 because our system was rainfed, runoff (*RO*) was ignored because the experimental sites were all flat and no *RO* was observed, and drainage (*D*) and capillary rise (*CR*) were not monitored and were both assumed negligible.

$$ET_{c-wx} = K_c ET_o \tag{Equation 5}$$

$$K_c = K_{cb} + K_e$$

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

$$ET_{c-wx} = (K_{cb} + K_e)\frac{0.408\,\Delta\,(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{Equation 6}$$

where

Kcb = basal crop coefficient, *Ke* = soil water evaporation coefficient (dimensionless), R_n = net radiation at the crop surface (MJ m^{-2} d^{-1}), G = soil heat flux density (MJ m^{-2} d^{-1}), T = daily air temperature (°C) at 2 m height, u_2 = wind speed (m s^{-1}) at 2 m height, e_s = saturation vapor pressure (kPa), e_a = actual vapor pressure (kPa), Δ = slope vapor pressure curve (kPa °C^{-1}) and γ = psychrometric constant (kPa °C^{-1}). We used the SIMDualKc platform (Rosa, Paredes, Rodrigues, Alves, et al., 2012; Rosa, Paredes, Rodrigues, Fernando, et al., 2012) to facilitate de calculation of ETc-wx.

The water use of cover crop mixes (ETc_{mx}; CRCC and CRCCFR) was calculated as the ratio of the water use (ETc_{mo}) to the biomass of the monocrop ($Biomass_{mo}$) CR (both obtained in our trials) multiplied by the biomass of the mix cover crop ($Biomas_{mx}$), as in eq. 7. Our approach was based on the well known relationship between grain biomass and water use (Steduto et al., 2012), often used in studies related to crops response to water (Garcia y Garcia et al., 2009).

$$ETc_{mx} = Biomass_{mx} \frac{ETc_{mo}}{Biomass_{mo}} \qquad \text{Equation 7}$$

The WUE (kg m^{-3}; eq. 8) of crops (corn, soybean, and cover crops) was obtained as the ratio of grain or biomass yield (kg ha^{-1}) to the water needed (ETc; mm) from each crop to make that yield.

$$WUE = \frac{Yield}{ET_C} \qquad \text{Equation 8}$$

STATISTICAL ANALYSIS

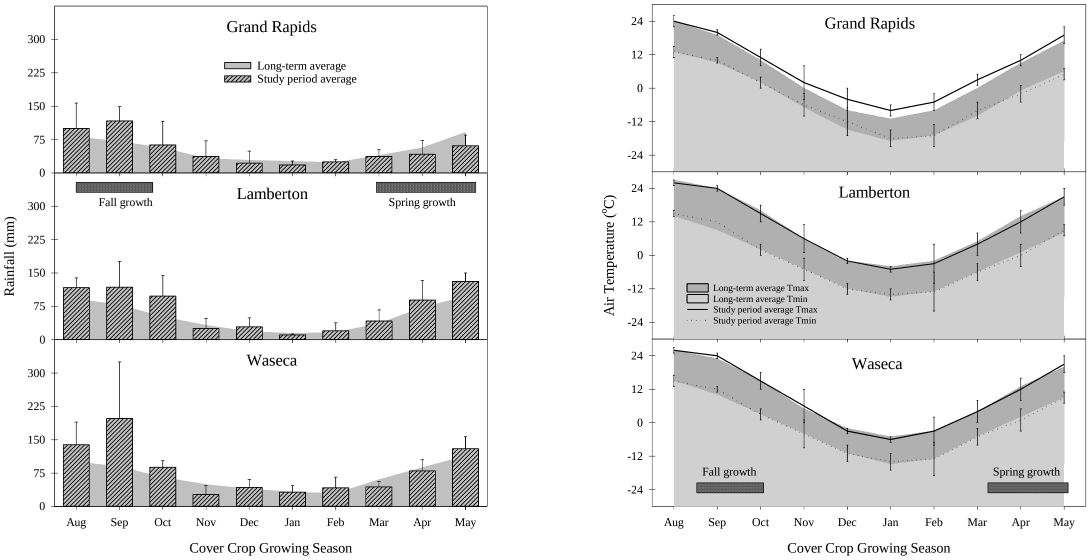
The statistical analysis was conducted using SPSS 20.0 for Windows (IBM Corporation, Armonk, New York). Location, year, cover crop strategy and their interaction were considered fixed effects while replication was considered a random effect for the analysis of yield, soil moisture and WU of primary crops and cover crops. Mean separation was performed using Fisher's least significant difference (LSD) test at P < 0.05.

RESULTS AND DISCUSSION

WEATHER CONDITIONS

The study period (2016-2019) was drier and warmer at Grand Rapids, but wetter and cooler at Lamberton and Waseca. Compared to the LTA conditions, the period of cover crops growth from seeding to establishment (mid-August to early-October) was wetter and cooler at all three locations, but slightly warmer at Grand Rapids and Waseca and slightly cooler at Lamberton (Chapter 4\Results and Discussion\Weather Conditions).

The cover crops spring growth period (mid-March to early-May) tended to be drier and warmer at Grand Rapids, and wetter and cooler at Lamberton and Waseca (Figure 6.1). The corn and soybean growing seasons (May – September) were warmer at Grand Rapids, wetter and cooler at Lamberton, and drier and cooler at Waseca; the driest month was July at Grand Rapids and June at Lamberton and Waseca, while June was the warmest month at all three locations. About 75% of rainfall fell during the primary crops growing season, most from June to September, indicating sufficient water for crops growth at all three locations (Rusch et al., 2020).



(a) (b)

Figure 6.1 Average a) precipitation and b) air temperature during the experimental years of the cover crops growing season as compared to the long-term average (LTA) at Grand Rapids, Lamberton, and Waseca, MN

The ET_o, a measure of the demand for water due to weather conditions, increased from May to August and peaked and decreased thereafter. In most years over the three locations, ET_o was below precipitation, reflecting the wetter conditions observed during the study period. For example, ET_o was above precipitation in 2018 at Grand Rapids and in 2017 at Lamberton only, suggesting potential water limitations to crops during those years. Averaged over six location-years, the daily ET_o was 0.10 in/d (2.8 mm d^{-1}) at Grand Rapids and 0.14 in/d (3.5 mm d^{-1}) at Lamberton and Waseca. The average total ET_o across growing seasons vary from 19.7 to 23.4 in (501 to 594 mm) at Grand Rapids, 24.1 to 25.8 in (613 to 665 mm) at Lamberton, and 23.3 to 26.0 in (593 to 659 mm) at Waseca (Figure 6.2).

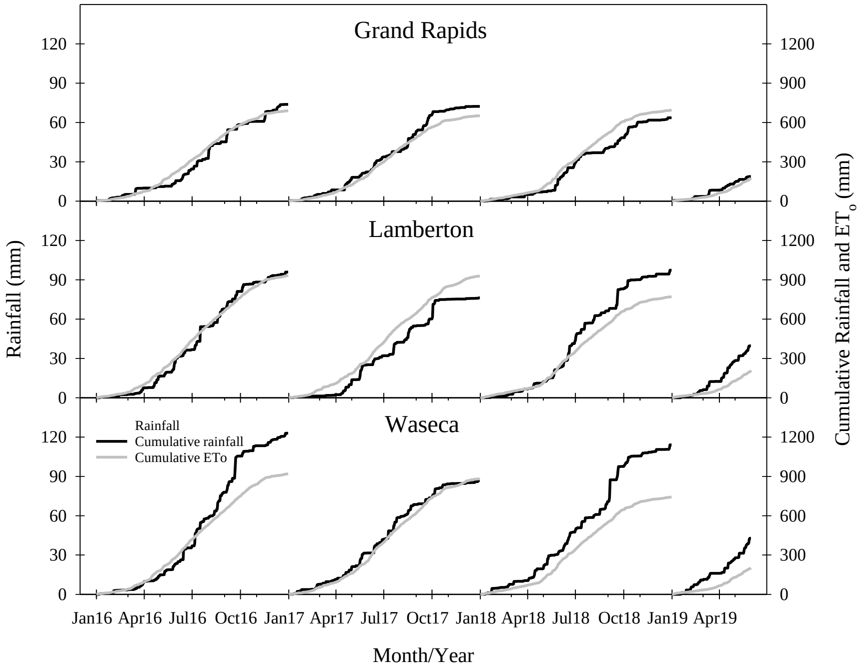


Figure 6.2 Rainfall, cumulative rainfall, and cumulative ETo at the study locations from 2016 to 2019.

SEASONAL SOIL WATER CONTENT

Soil moisture from both corn and soybean plots was affected by the location x year interaction, only (Table 6.1). Differences in soils and weather conditions may explain such effects.

Table 6.1 Significance of fixed sources of variation for grain yield of corn and soybean, biomass of cover crops, and soil moisture

Fixed Source of Variation	**Yield**			**Soil Moisture**
	Corn	*Soybean*	*Cover Crops Biomass*	
Year (Y)	**	**	**	ns
Location (L)	**	**	**	**
Cover Crops (C)	ns	ns	ns	ns
Y×L	**	**	**	**
Y×C	ns	ns	ns	ns
L×C	ns	ns	ns	ns
Y×L×C	ns	ns	ns	ns

* Significant difference ($P < 0.05$); ** highly significant difference ($P < 0.01$); ns denotes no difference.

Soil moisture increased with depth at all three locations, with greater variation in the top 8 inches soil. Soil moisture in the 12-16 in layer was close to 50% at Waseca, suggesting that soil conditions were near or at saturation. These results are the consequence of textural differences (see chapter 1 for soil characteristics) and precipitation pattern (Figure 6.2) across locations. Soil moisture at cover crops seeding (late summer to early fall) was usually lower than at spring termination, except at Waseca in 2016 (Table 6.2), when heavy rainfall two days before seeding cover crops exceeded 5.9 in (150 mm). Our results support those by Daigh et al. (2014), who reported that CR cover crop in corn-soybean rotation for conditions in Iowa and Indiana, U.S. did not affect soil moisture.

Table 6.2 Volumetric soil water content at seeding and termination of cover crops

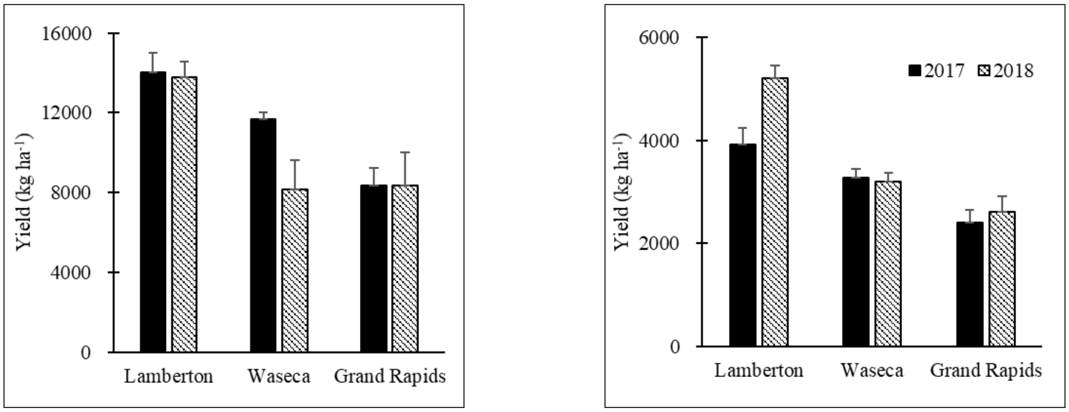
Location	**Soil depth (inch)**	**Volumetric Soil Water Content (%)§**					
		Seeding (late summer-early fall)			Termination (early Spring)		
		2016	*2017*	*2018*	*2017*	*2018*	*2019*
Grand Rapids	4	20.1±1.6	26.8±1.6	19.9±1.6	26.4±1.7	19.1±2.1	20.8±2.9
	8	24.5±1.6	30.5±2.0	24.4±1.0	30.4±2.3	26.5±1.7	21.6±0.3
	12	27.3±2.7	31.7±1.6	26.4±2.1	30.2±2.8	30.8±3.0	32.9±1.8
	16	28.8±2.6	33.0±2.2	25.3±2.0	31.9±1.7	28.9±2.2	35.5±2.1
Lamberton	4	27.3±3.6	25.7±2.4	18.4±2.2	28.0±1.2	28.4±1.8	27.2±1.4
	8	36.5±2.2	31.0±1.6	22.7±4.0	33.7±0.8	35.9±1.0	32.9±0.6
	12	37.6±3.2	37.2±1.6	29.7±4.3	36.6±1.2	38.5±1.7	38.3±1.0
	16	39.5±2.6	40.4±2.6	37.8±4.3	39.2±1.2	44.0±2.1	44.3±1.3
Waseca	4	30.4±1.3	23.3±2.3	27.0±4.5	30.0±0.3	32.0±1.1	31.4±0.7
	8	38.4±1.3	29.6±3.7	31.1±3.8	35.2±0.7	34.9±1.5	34.0±0.6
	12	41.8±3.2	36.2±3.3	37.6±1.9	39.5±1.2	41.5±1.7	40.9±1.1
	16	49.3±3.5	46.7±4.1	40.5±3.3	48.0±1.9	47.7±1.8	47.9±0.8

§ Average volumetric water content ± standard error

PRODUCTIVITY OF CROPS AND COVER CROPS

Yield of corn and soybean was significantly affected by year, location, and their interactions, but was not affected by cover crops. However, corn and soybean yields from the no cover crop treatments were, respectively, 3% and 1% higher compared to those from plots with cover crops (Rusch et al., 2020). Both corn and soybean yields were lowest at Grand Rapids and highest at Lamberton (Figure 6.3), mainly due to shorter season genotypes used in the former.

Cover crops biomass was highly variable, and significantly affected by year, location, and their interaction, but not affected by cover crops (Table 6.1). Similarly, Restovich et al. (2012) report high variability of cover crop biomass among species and years for conditions in the humid pampas region of Argentina. In our study, biomass of all cover crops was much higher in the first year (fall 2016 and spring 2017) than in the following years at all three locations (Rusch et al., 2020). The reason for this large variation was mainly due to extreme weather conditions, specifically very cold and prolonged winters and heavy rainfalls in spring and fall (Rusch et al., 2020). The effect of such constraints are reported to have severely affected the establishment of a CR cover crop for conditions in Iowa (Qi & Helmers, 2010). During our study period, the average minimum temperature for the first, second and third year from September to May was 25.2, 18.7 and 18.0 F (-3.8, -7.4, -7.1°C) at Grand Rapids; 27.7, 30.0, and 20.8 (-2.4, -1.2, -6.2°C) at Lamberton; and 29.7, 21.2, 21.6 F (-1.3, -6, -5.8°C) at Waseca.



(a) Corn (b) Soybean

Figure 6.3 Experimental yield of corn and soybean during the 2017 and 2018 growing seasons.

EVAPOTRANSPIRATION OF CROPS AND COVER CROPS

ACCURACY OF ESTIMATIONS

The accuracy of our water balance estimations was determined using correlation analysis between *ETc-wb* and *ETc-wx*; the former from observed soil moisture and the latter from weather data. Although both approaches showed a strong correlation (Figure 6.4), the ETC-wb approach under-estimated the water use of crops, mostly because we did not consider drainage in our calculations.

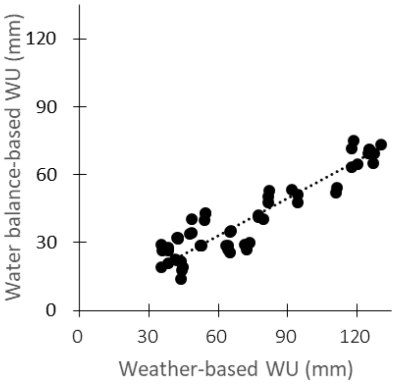


Figure 6.4 Correlation between calculated (*ETc-wx*) and estimated (*ETc-wb)* water use of crops and cover crops.

WATER USE OF CROPS AND COVER CROPS

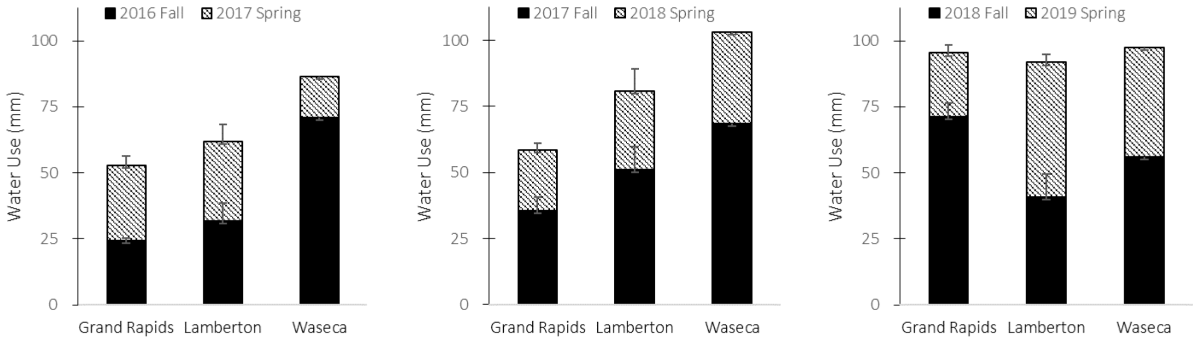
Except for the water use of cover crops in spring, the water use of crops and cover crops was significantly affected by year, location, and their interaction. Cover crop strategy did not affect the water use of crops and cover crops (Table 6.3).

Table 6.3 Significance of fixes sources of variation for water use of corn, soybean and cover crops.

Fixed Source of Variation	**Water Use**			
	Corn	*Soybean*	*Cover Crops-Fall*	*Cover Crops- Spring*
Year (Y)	**	**	**	ns
Location (L)	**	**	**	**
Cover Crop Strategy (C)	ns	ns	ns	ns
Y×L	**	**	**	**
Y×C	ns	ns	ns	ns
L×C	ns	ns	ns	ns
Y×L×C	ns	ns	ns	ns

** Highly significant difference (P < 0.01); * significant difference (P < 0.05); ns denotes no difference.

Cover crops WU in year one during either fall or spring was around 1.0 and 1.1 inches (24 and 28 mm) at Grand Rapids, 1.3 and 1.2 inches (32 and 30 mm) at Lamberton, and 2.8 and 0.6 inches (71 and 16 mm) at Waseca. Cover crop WU in year two was 2.8 and 1.0 inches (71 mm and 24 mm) at Grand Rapids, 1.6 and 2.0 inches (40 and 50 mm) at Lamberton, and 2.2 and 1.6 inches (56 and 41 mm) at Waseca (Figure 6.5). Excess rainfall may explain the higher water use in fall as compared to spring.



(a) 2016-2017 (b) 2017-2018 (c) 2018-2019

Figure 6.5 Fall, spring, and total water use of cover crops late-interseeded into corn and soybean during three growing season in the upper Midwest U.S.

Most water used by cover crops corresponded to evaporation. The *ETc-wx* showed that soil evaporation accounted for about 70% of the total evapotranspiration in fall and 60% of in spring (Figure 6.6). These results support our findings of marginal growth and soil coverage, which resulted in high soil evaporation. Our results are in agreement with reported evaporation rates from soil with low vegetation coverage (Silva et al., 2012). Our results support Ward et al. (2012) findings that cover crops have limited effect on evaporation rates during early growth and on the soil water balance, but may still increase the sustainability of the agroecosystem.

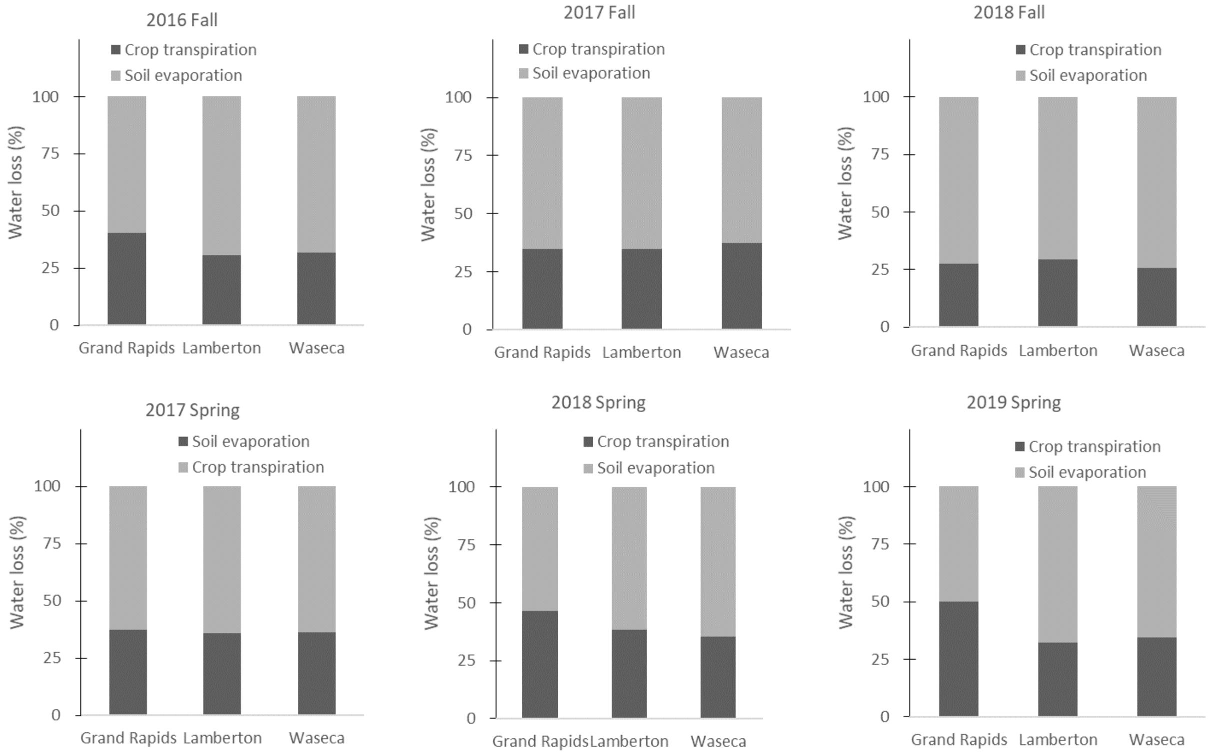
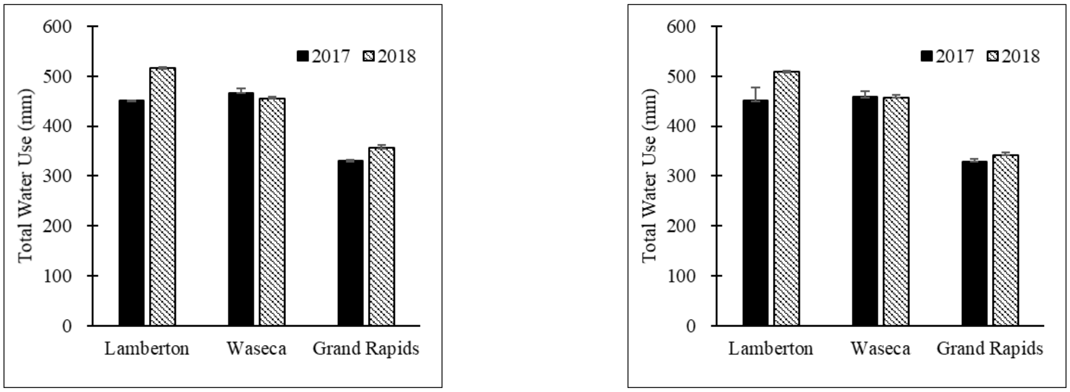


Figure 6.6 Contribution of evaporation and transpiration in the evapotranspiration of cover crops during the spring of 2017, 2018, and 2019 at three locations in MN.

The average WU of corn in 2017 and 2018 was 13 and 14 in (330 and 356 mm) in Grand Rapids, 17.8 and 20.3 in (451 and 516 mm) in Lamberton, 18.4 and 17.9 in (467 and 455 mm) in Waseca, respectively. The average WU of soybean in 2017 and 2018 was 13 and 13.4 in (329 and 341 mm) at Grand Rapids, 17.7 and 20.0 in (451 and 509 mm) at Lamberton, and 18 in (458 mm) at Waseca, respectively (Figure 6.7). Our results are typical of the region and similar to those reported in previous studies (Garcia y Garcia & Strock, 2018; Irmak et al., 2014). Averaged over six site-years, the WU of corn and soybean from this study were similar, which is in agreement with previous studies on year-to-year water use comparison of corn and soybean reporting that both crops have similar water requirements . For example, Hussain et al. (2019), report no consistent difference in WU of no-tilled rainfed corn and soybean during three growing seasons in Michigan, U.S.

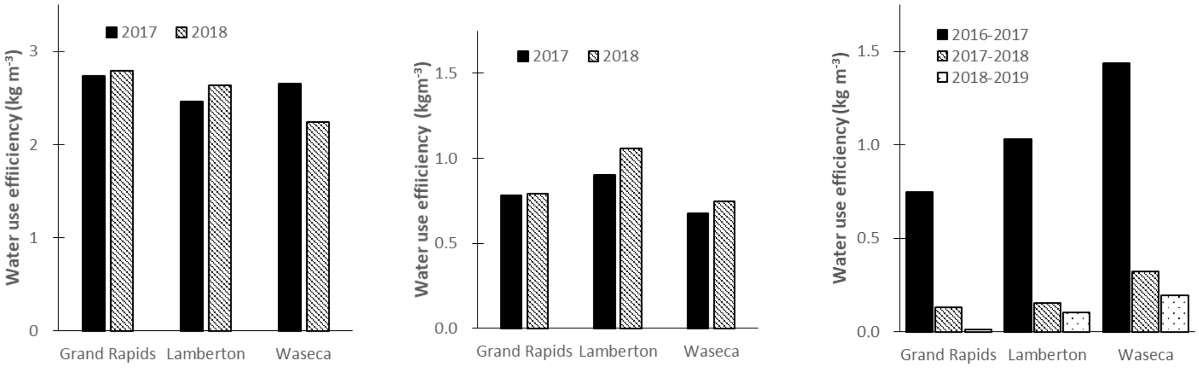


(a) Corn (b) Soybean

Figure 6.7 Water use of corn and soybean during the 2017 and 2018 growing seasons

WATER USE EFFICIENCY OF CROPS AND COVER CROPS

Average WUE of corn was 592, 685, 577 lb/inch (2.62, 3.03, 2.55 kg m^{-3}) in 2017 and 531, 592 and 427 lb/inch (2.35, 2.62, and 1.89 kg m^{-3}) in 2018 at Grand Rapids, Lamberton, and Waseca, respectively. Similarly, the WUE of soybean was 176, 204, and 154 lb/inch (0.78, 0.9, and 0.68 kg m^{-3}) in 2017 and 179, 240, and 170 lb/inch (0.79, 1.06, and 0.75 kg m^{-3}) in 2018 at Grand Rapids, Lamberton, and Waseca, respectively (Figure 6.8). These results support those from Singh et al. (2014) and Hussain et al. (2019), who report comparable WUE of rainfed corn in Canada and Michigan, respectively. Similarly, our results support those from Irmak et al. (2014) and Hussain et al. (2019), who report similar WUE of rainfed and irrigated soybean in Nebraska, U.S. and Ontario, CA, respectively.



(a) Corn (b) Soybean (c) Cover crops

Figure 6.8 Water use efficiency of corn and soybean in 2017 and 2018, and cover crops during 2016-2017, 2017-2018, and 2018-2019 growing seasons.

The WUE of the cover crops was greatly affected by year, and location. The cover crops WUE varied from 357 to 16 lb DM/inch (1.58 to 0.07 kg m^{-3}) at Lamberton, 215 to 20 lb DM/inch (0.95 to 0.09 kg m^{-3}) at Waseca, and 111 and 2.3 lb DM/inch (0.49 to 0.01 kg m^{-3}) at Grand Rapids (Figure 6.8). The large variation on WUE was due to variations on aboveground biomass production because of weather conditions (Rusch et al., 2020).

CONCLUSIONS

We found that cover crops seeded late in the corn and soybean growing season did not affect soil moisture dynamics and yield of primary crops.

The water use and water use efficiency of corn and soybean were both markedly affected by year, location, and the year x location interaction, but were not affected by cover crops. Both crops had similar WU, averaging over six location-years ~14 and 13.6 inches (353 and 346 mm) for corn and soybean, respectively. Similarly, water use efficiency of corn and soybean averaged over six location-years was 696 and 234 lb DM/inch (3.07 and 1.03 kg m^{-3}), respectively.

The water use of cover crops was affected by year, locations, and the year x location interaction, but was not affected by the cover crop strategy. During both fall and spring, soil evaporation was the major component of cover crops water use, averaging about 70% across locations. The WUE of cover crops did not vary among strategies, but it was highly affected by location, year, and their interaction, ranging from as little as 2.3 lb DM/inch (0.01 kg m^{-3}) to as high as 357 lb DM/inch (1.58 kg m^{-3}) across all locations.

This study covered three locations in the U.S. upper Midwest, where growing seasons are typically short. Our findings should apply to similar regions cover crop management practices (late-interseeded in corn and soybean), and perhaps to other northern locations. While cover crops may affect soil moisture and the water use and yield of primary crops, results from this study demonstrated that late interseeded cover crops in a northern location did not have such effect.

CHAPTER 7 – COVER CROPS AT MULTIPLE LOCATIONS: EFFECT OF INTERSEEDED COVER CROPS ON INSECT PEST, PREDATOR, AND PARASITOID POPULATIONS

ABSTRACT

We studied the effect of cover crops in pest and natural enemy (predators and parasitoids) population dynamics in corn at three location in Minnesota. Our objectives were to determine the abundance of pest, parasitoids and predators in cornfields with early-interseeded (at V4-V6) cover crop strategies. At all location-years, the abundance of pest, parasitoids, and predators was affected by sampling date but was not affected by cover crop strategy. Most pests collected included western corn rootworm, northern corn rootworm, and tarnished plant bugs. Among locations, the abundance of pests was higher at Lamberton, followed by Waseca and Grand Rapids. In 2017, the number of pests collected was affected by sampling date while cover crops had no effect. In 2018, neither cover crops nor sampling date affected the number of pests in Grand Rapids and Lamberton; sampling date, however, affected the population of pests collected. At Waseca, pest population was not affected by either sampling date or cover crop strategy. Most parasitoids collected included Braconids and Ichneunmonids. Parasitoids were more abundant at Lamberton and Waseca in 2017 and at Grand Rapids in 2018. The number of parasitoids collected was significantly affected by sampling date; cover crops, however, had no effect on parasitoids abundance at all locations. Most predators found in the study included Chrysopids, Syrphids, Signal, Long legged, Pirate bug, Spider and Coccinellidae. Predators were more abundant at Grand Rapids in 2017 and similar at all three locations in 2018. Predators collected with the pitfall traps were more abundant at Waseca, followed by Lamberton and Grand Rapids. At any location/year, sampling date significantly affected the population of predators collected while cover crops did not affect the population of predators. Predators collected with pitfalls included arachnids and ground beetles. Neither cover crops nor sampling date affected the number of predators collected with pitfalls at Grand Rapids while at Lamberton and Waseca the number of predators from pitfalls was affected by sampling date only.

Keywords: pests, predators, parasitoids, cover crops

INTRODUCTION

Minnesota planted over 8 million acres of corn (*Zea mays* L.) in 2020 (USDA-NASS, 2020c). Cover crops use in corn production systems is increasing, and so the interest for a better understanding of the potential contribution of the practice to sustainability. The multiple ecosystem services of cover crops include improvement of soil properties and crop productivity (Blanco-Canqui et al., 2015), enhancement of food resources for pollinators (Eberle et al., 2015), and beneficial insects like natural predators and parasitoids helping in pest suppression (Altieri & Nicholls, 2018; Reeves, 1997), among others.

In Minnesota, several cover crop strategies have been studied in corn-soybean rotations to understand their effect on productivity of primary crops and the environment (Rusch et al., 2020). Earlier studies have showed that cover crops influence the reduction of herbivore abundance compared to monocultures (Andow, 1991; Letourneau et al., 2011; Root, 1973). Such findings evidence the potential of cover crops as strategy for pest management (Costamagna & Landis, 2006; Desneux et al., 2006; T. B. Fox et al., 2005) by reducing colonization or by increasing natural enemy densities (Koch et al., 2012). This is because cover crops increase landscape heterogeneity and reduce agricultural intensification that in turn helps reducing herbivore density (Andow, 1991; Landis et al., 2000; H. A. Smith & McSorley, 2000).

Among the number of key insects in corn, western corn rootworms (*Diabrotica virgifera virgifera* LeConte) and northern corn rootworm (*Diabrotica barberi* Smith & Lawrence) have long been considered as challenging pests in the north-central USA (Wilde et al., 1972). Rootworm eggs, for example, Although early studies suggest winter soil temperature of 18.5°F at 3–6 inches depth as the lower limit below which significant mortality of eggs occurs (Gustin, 1981), certain proportion of rootworm eggs survive the harsh winter conditions of the region that are liable to cause economic damage (Ellsbury & Lee, 2004).

Cover crops may be a consistent, abundant, and well disseminated alternative food source and microhabitat favorable to the diverse community of natural enemies (Altieri and Nicholls, 2004). For example, cover crops in corn and soybean fields have shown to increase the abundance of predatory carabid beetles and the consumption of European corn borer (*Ostrinia nubilalis* Hübner) pupae (Prasifka et al., 2006). In conservation tillage cotton cover crops have been found to increase predator population, including lady beetles and fire ants, resulting in the reduction of heliothine pest population compared to control (Tillman et al., 2004). Some groups of predators like spiders, mites, and beetles feed on plant material, and their abundance could be helpful in the management of minor and major pests. It’s reported that the abundance of dipterans belonging to families Syrphidae (MacLeod, 1999) and Tachinidae (Platt et al., 1999) as well as parasitoids (Begum et al., 2006; Jervis et al., 1993; Patt et al., 1997; Stephens et al., 1998) has increased in response to flowering plants that provide pollen and nectar.

We used a multi-location experiment (Rusch et al., 2020) to study the effect of cover crops in pest and natural enemy (predators and parasitoids) population dynamics in corn. Our objectives were to determine the abundance of pest, parasitoids and predators in cornfields with cover crops interseeded at V4-V6 corn stages of development.

MATERIAL AND METHODS

The general procedure for this trial is described in Chapter 1, Methods and Timeline section. These include description of locations, experimental design, management, data collection, and statistical analysis. Procedures not described in Chapter 1 are detailed under this section.

THE EXPERIMENTS

We monitored populations of pests, parasitoids, and predators in corn with early-interseeded (V4-V6) cover crops. Studies were nested in Rusch et al. (2020) experiments conducted at three different locations in Minnesota. We collected data during the 2017 and 2018 growing seasons. The first experiment (2017-2018) was set to monitor pests, parasitoids, and predators with yellow sticky traps (hereafter referred to as *yellow sticky trap study*). The second experiment (2018) was set to monitor predators with pitfall traps (hereafter referred to as *pitfall trap study*). Both studies were initiated after cover crops seeding. The studies were conducted at the University of Minnesota Research and Outreach Centers in Grand Rapids (47˚18’N; - 93˚53’W), Lamberton (44˚24’N; -95˚31’W), and Waseca (44˚06’N; -93˚53’W), Minnesota.

DATA COLLECTION

Pherocon AM unbaited yellow sticky traps were placed on one of two middle rows attached to corn stems (Figure 9.5). We used two traps per plot initially placed at 14-16 inch height on ear-leaf and moved slightly higher as needed to facilitate data collection. The sticky traps were 8.5 in x 11 gridded sheets made of tagboard and stayed in the field for approximately one week before they were collected. Few sticky traps were lost due to wind, which were discarded. Pitfall traps consisted on plastic cups with detergent water (a cup within a cup, so the same spot sampled) placed in the soil in between the two middle rows of each plot and covered with a piece of cardboard held slightly above the cup with a screw to prevent debris from falling into the cup. We collected trapped specimens 24 hours later.

DATA ANALYSIS

Results from the *yellow sticky trap study* were analyzed separately for each location and year. Results were grouped into pests, predators, and parasitoids depending upon the functional diversity. Data were transformed using log-transformation or power transformation to meet the normality and constant variance assumptions. The abundance of pests, predators, and parasitoids was analyzed using the ‘nlme’ package (Pinheiro et al., 2020) with date and location as fixed effect and replication as random. We performed anova using the ‘car’ package (J. Fox & Weisberg, 2018) and determine the significance among variables with the Tukey test using the ‘multcomp’ package (Hothorn et al., 2008) at the 95% confidence. We performed a multivariate analysis of variance (MANOVA) to determine the overall effect of date and cover crop strategy on insect groups collected from the *pitfall trap study*. All analyses were performed using R statistical software version 3.6.3 (R Core Team 2020).

RESULTS AND DISCUSSION

WEATHER CONDITIONS

Weather conditions during the experimental years were as described under Chapter 4\Results and Discussion\Weather Conditions.

YELLOW STICKY TRAP STUDY

ABUNDANCE OF PESTS

Most pests collected in 2017 and 2018 at all three locations included western corn rootworm, northern corn rootworm, and tarnished plant bugs *Lygus lineolaris* (Palisot de Beauvois) (Insecta: Hemiptera: Miridae). At all locations in 2017, the number of pests collected was significantly affected by sampling date (P = 0.0001 within each location), but cover crops did not affect pest populations. In 2017, the average pest population was lower at Grand Rapids and higher at Lamberton (Figure 7.1). In 2018, neither cover crops nor sampling date affected the number of pests in Grand Rapids and Lamberton; sampling date, however, affected the population of pests collected in Waseca.

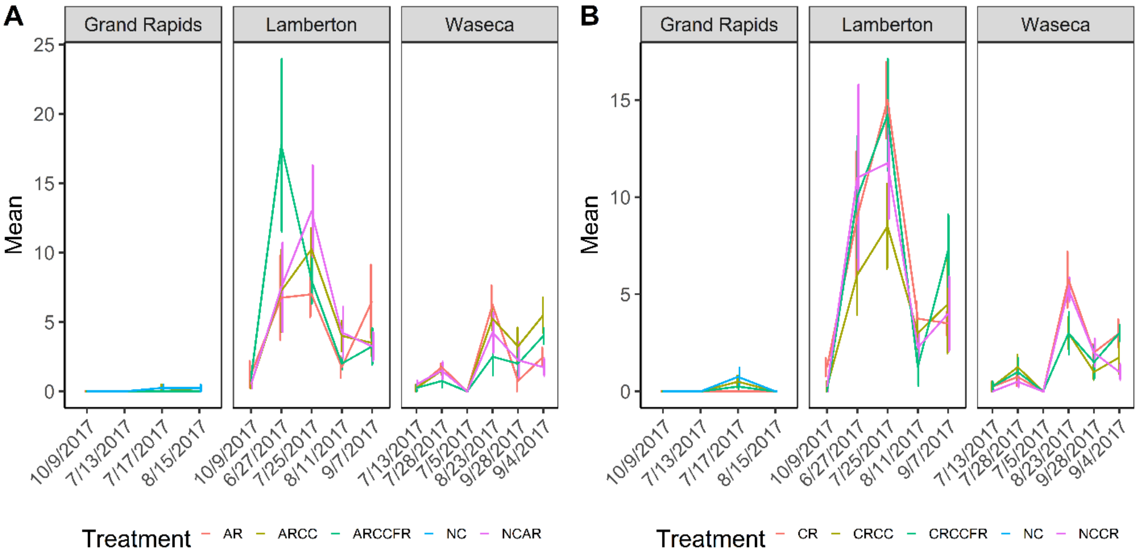


Figure 7.1 Mean number of pests from yellow sticky trap in (A) AR- and (B) CR-based cover crop strategies at Waseca, Lamberton, and Grand Rapids across different dates in 2017. Vertical lines denote the SE.

ABUNDANCE OF PARASITOIDS

In both years, parasitoids collected included Braconids and Ichneunmonids; number of parasitoids was lower at Grand Rapids and higher at Lamberton in 2017, and higher at Grand Rapids and lower at Waseca in 2018 (Figure 7.2). Population of parasitoids observed was significantly affected by sampling date (P < 0.001 at each location/year). During both years and at all three locations, cover crops had no effect on parasitoids population.

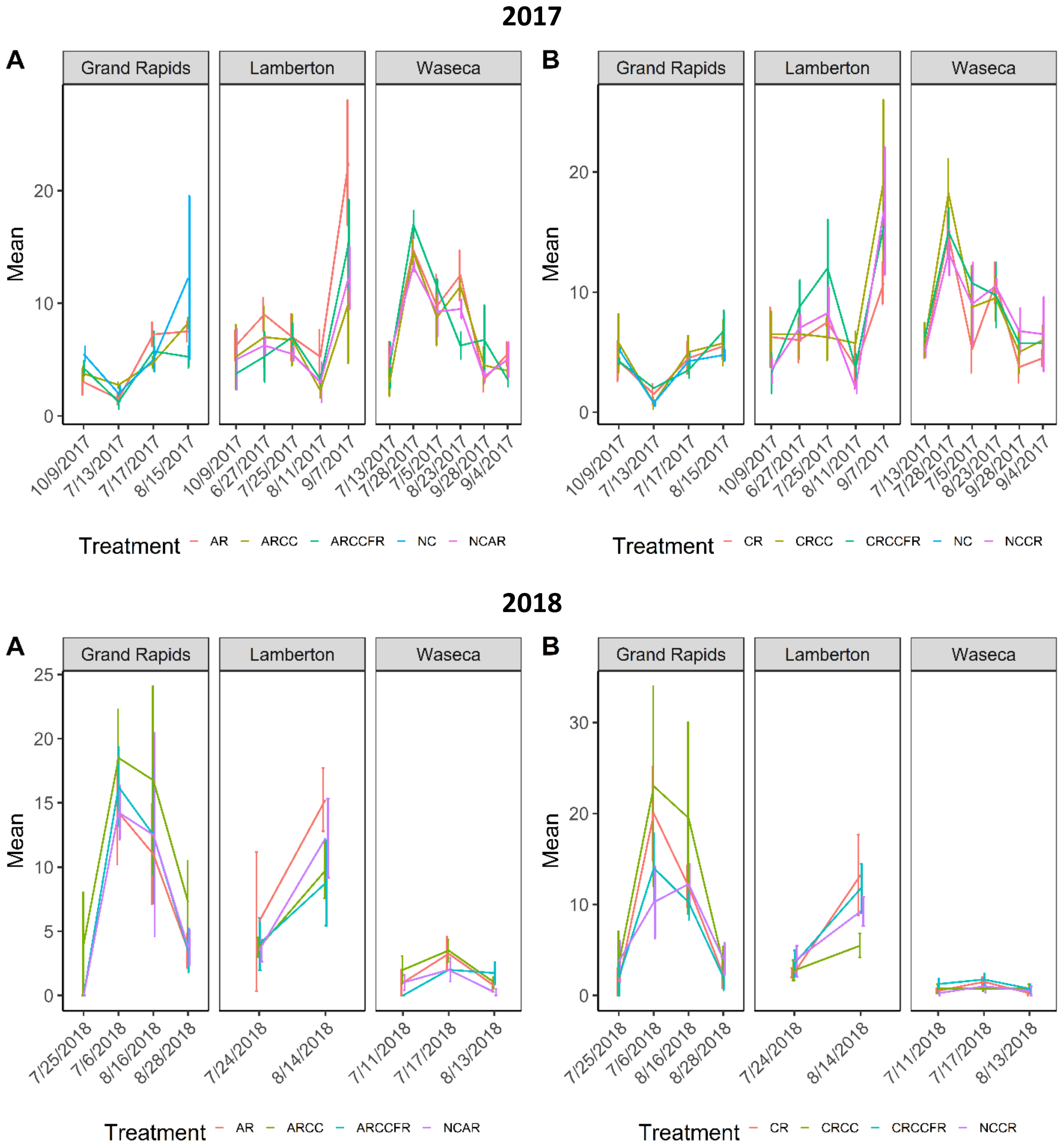


Figure 7.2 Mean number of parasitoids from yellow sticky trap in (A) AR- and (B) CR-based cover crop strategies at Waseca, Lamberton, and Grand Rapids across different dates in 2017 and 2018. Vertical lines denote SE.

ABUNDANCE OF PREDATORS

Most predators found in our study included Chrysopids, Syrphids, Signal, Long legged, Pirate bug, Spider and Coccinellids. Averaged over years, predator population was lower at Grand Rapids and higher at Waseca (Figure 7.3). At any location/year sampling date significantly affected the population of predators collected (P < 0.001 at each location); cover crops did not affect the population of predators.

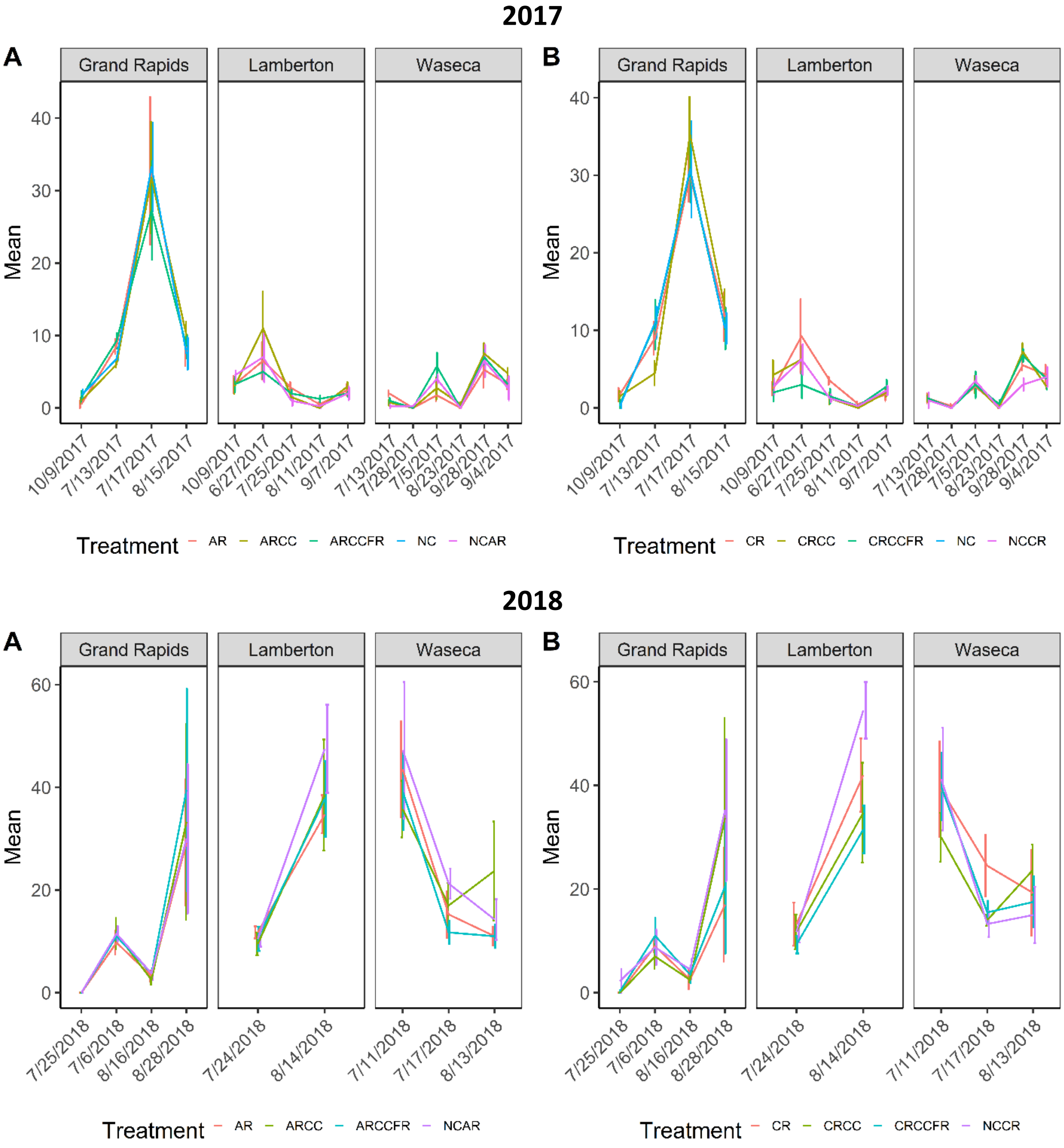


Figure 7.3 Mean number of predators collected from yellow sticky trap study in (A) AR- and (B) CR-based cover crop strategies at Waseca, Lamberton, and Grand Rapids across different dates in 2017 and 2018. Vertical lines denote the standard error of the mean.

PITFALL TRAP STUDY

Overall, the abundance of predators collected with the pitfall traps was highly variable across cover crop strategies and sampling dates. We did not find a discernible cover crop x predator association, so, our results may reflect the inherent variability expected in cornfields without cover crops. We speculate that these results reflect the overall poor growth of cover crops reported by Rusch et al. (2020).

Predators collected included arachnids and ground beetles. Neither cover crops nor sampling date affected the number of predators collected at Grand Rapids (P = 0.08). The number of predators was affected by sampling date at Lamberton and Waseca.

At Grand Rapids, both arachnids and ground beetles were more abundant by mid-August; in end-August, arachnids were less abundant and no ground beetles were collected (Table 7.1). At Lamberton, arachnids and ground beetles were more abundant early- and late-July, respectively, and less abundant or not present by early-September (Table 7.2). Similar to Lamberton, arachnids at the Waseca site were more abundant early-July, but ground beetles were more abundant in early-August (Table 7.3).

Table 7.1 Mean (± SE) number of predators at Grand Rapids across cover crop strategies and sampling dates in 2018

Treatment§	**Sampling Date**				
	7/18	7/6	8/10	8/17	8/29
Arachnids					
AR	1.00 ± 0.58	0.50 ± 0.29	1.00 ± 0.41	1.75 ± 0.25	1.00 ± 0.41
ARCC	0.50 ± 0.29	0.50 ± 0.29	1.25 ± 0.75	2.25 ± 0.63	1.00 ± 0.58
ARCCFR	0.75 ± 0.48	1.00 ± 0.00	0.75 ± 0.75	1.75 ± 0.48	1.00 ± 0.71
ARNC	1.75 ± 0.25	1.00 ± 0.41	0.25 ± 0.25	1.75 ± 0.63	0.50 ± 0.29
CR	0.50 ± 0.50	1.00 ± 0.71	0.00 ± 0.00	1.00 ± 0.58	1.00 ± 0.58
CRCC	1.25 ± 0.48	0.75 ± 0.48	0.50 ± 0.29	0.25 ± 0.25	0.25 ± 0.25
CRCCFR	1.25 ± 0.25	1.00 ± 0.58	1.50 ± 0.50	1.25 ± 0.75	0.75 ± 0.48
CRNC	0.25 ± 0.25	0.25 ± 0.25	0.25 ± 0.25	1.00 ± 0.71	1.00 ± 0.41
Ground beetle					
AR	0.50 ± 0.29	0.25 ± 0.25	0.25 ± 0.25	1.00 ± 0.71	0.00 ± 0.00
ARCC	1.00 ± 0.71	0.75 ± 0.25	0.75 ± 0.48	3.75 ± 1.03	0.00 ± 0.00
ARCCFR	0.00 ± 0.00	0.00 ± 0.00	0.75 ± 0.48	2.50 ± 1.19	0.00 ± 0.00
ARNC	0.00 ± 0.00	0.50 ± 0.29	0.00 ± 0.00	1.75 ± 0.85	0.00 ± 0.00
CR	1.25 ± 0.63	0.00 ± 0.00	0.50 ± 0.29	2.00 ± 0.41	0.00 ± 0.00
CRCC	1.25 ± 0.48	0.25 ± 0.25	0.50 ± 0.50	3.25 ± 0.48	0.00 ± 0.00
CRCCFR	0.00 ± 0.00	0.75 ± 0.75	1.00 ± 0.41	1.75 ± 0.25	0.00 ± 0.00
CRNC	0.00 ± 0.00	0.00 ± 0.00	0.25 ± 0.25	0.75 ± 0.25	0.00 ± 0.00

§AR = Annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye

Table 7.2 Mean (± SE) number of predators at Lamberton across cover crop strategies and sampling dates in 2018.

Treatment[§]	Sampling Date			
	7/10	7/24	8/14	9/7
		Arachnids		
AR	1.50 ± 0.65	1.25 ± 0.95	0.25 ± 0.25	1.75 ± 1.18
ARCC	1.75 ± 0.25	0.25 ± 0.25	0.25 ± 0.25	1.25 ± 0.63
ARCCFR	3.50 ± 1.76	0.75 ± 0.48	0.25 ± 0.25	0.75 ± 0.48
ARNC	3.00 ± 0.41	1.25 ± 0.75	1.00 ± 1.00	1.00 ± 0.41
CR	1.50 ± 0.96	0.00 ± 0.00	0.25 ± 0.25	0.25 ± 0.25
CRCC	2.25 ± 1.60	0.00 ± 0.00	0.25 ± 0.25	0.75 ± 0.48
CRCCFR	2.75 ± 1.89	0.50 ± 0.50	0.50 ± 0.29	0.50 ± 0.29
CRNC	1.25 ± 0.48	0.00 ± 0.00	0.25 ± 0.25	0.00 ± 0.00
		Ground beetle		
AR	0.00 ± 0.00	1.00 ± 0.71	0.50 ±0.29	0.00 ± 0.00
ARCC	1.00 ± 0.41	1.00 ±0.71	0.25 ± 0.25	0.00 ± 0.00
ARCCFR	0.50 ± 0.29	1.00 ±0.58	0.75 ± 0.25	0.00 ± 0.00
ARNC	0.50 ± 0.29	1.5 ± 0.96	0.25 ± 0.25	0.00 ± 0.00
CR	0.00 ± 0.00	0.50 ± 0.50	0.50 ± 0.50	0.00 ± 0.00
CRCC	0.75 ± 0.48	1.00 ± 0.71	0.75 ± 0.75	0.00 ± 0.00
CRCCFR	0.25 ± 0.25	0.75 ± 0.48	0.50 ± 0.29	0.00 ± 0.00
CRNC	0.75 ± 0.25	0.25 ± 0.25	0.25 ± 0.25	0.00 ± 0.00

[§] AR = Annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye

Table 7.3 Mean (± SE) number of predators at Waseca across cover crop strategies and sampling dates in 2018.

Treatment[§]	Sampling Date			
	7/5	7/17	8/3	8/14
	Arachnids			
AR	5.00 ± 0.71	1.50 ± 1.19	1.75 ± 0.63	2.25 ± 0.85
ARCC	3.00 ± 0.91	2.25 ± 0.25	1.75 ± 0.48	1.75 ± 0.48
ARCCFR	4.25 ± 1.44	2.00 ± 0.58	1.00 ± 0.71	2.50 ± 0.50
ARNC	4.75 ± 1.25	2.25 ± 0.63	1.75 ± 0.75	2.50 ± 0.65
CR	2.25 ± 1.03	2.25 ± 1.25	1.75 ± 0.85	3.50 ± 0.29
CRCC	3.75 ± 1.75	1.00 ± 0.41	0.75 ± 0.75	2.00 ± 0.41
CRCCFR	2.50 ± 1.66	2.00 ± 1.08	1.25 ± 0.48	2.50 ± 0.87
CRNC	1.50 ± 0.87	1.50 ± 0.65	1.25 ± 0.48	1.00 ± 0.58
	Ground beetle			
AR	1.50 ± 0.50	2.00 ± 0.71	0.75 ± 0.25	1.75 ± 0.48
ARCC	1.25 ± 0.75	1.50 ± 0.65	2.25 ± 0.48	2.00 ± 1.08
ARCCFR	0.75 ± 0.48	1.25 ± 0.25	0.00 ± 0.00	0.75 ± 0.48
ARNC	1.50 ± 0.29	1.00 ± 1.00	3.75 ± 1.18	1.00 ± 0.71
CR	0.50 ± 0.50	0.50 ± 0.50	1.25 ± 0.25	1.00 ± 0.71
CRCC	1.25 ± 0.48	0.50 ± 0.29	2.00 ± 0.41	0.75 ± 0.25
CRCCFR	0.50 ± 0.50	1.25 ± 0.25	3.00 ± 0.91	2.25 ± 1.31
CRNC	2.50 ± 1.55	1.75 ± 0.75	0.75 ± 0.48	0.50 ± 0.29

[§] AR = Annual ryegrass, CC = crimson clover, FR = forage radish, CR = cereal rye

CONCLUSIONS

At all location-years, the abundance of pest, parasitoids, and predators was affected by sampling date but was not affected by cover crops.

Among locations, pests were more abundant in Lamberton, followed by Waseca and Grand Rapids. Parasitoids were more abundant at Lamberton and Waseca in 2017 and at Grand Rapids in 2018.

Predators were more abundant at Grand Rapids in 2017 and similar at all three locations in 2018. Predators collected with the pitfall traps were more abundant in Waseca, followed by Lamberton and Grand Rapids.

CHAPTER 8 – ECONOMIC ANALYSIS OF COVER CROP STRATEGIES IN CORN

ABSTRACT

The call for sustainable crop production has resulted in an increased interest in cover crops. In Minnesota, however, the adoption of the practice has been slow, though steadily increasing. Reasons for this slow adoption vary from its practicality due to weather conditions to its economic benefits. The economics of cover crops are complex, and more so in a region characterized by long winters and wet springs, which results in very short window opportunity for cover crops to grow enough and provide the agroecosystem services expected. That is, to take full advantage of their benefits. Moreover, ecosystem services are associated to time for gradual changes; therefore, time and management become important component to cover crop profitability. The objective of this study was to determine the profitability of overwintering and winterkilled cover crops early- and late-interseeded into corn grown under different tillage practices at multiple locations in Minnesota. Our results showed that none of the cover crop strategies used was economically viable. Our research suggested that early- and late-interseeded cover crops into corn could increase variable costs and reduce farm profits, at least in the short run. It's important to note that our economic analysis neither considered the possibility of N credit nor the potential environmental benefits (including enhanced soil health, biodiversity, reduction of NO_3-N in the leachate, among others) from cover crops use. The strategies evaluated in this project are just some of several others that should or could be investigated to determine which ones are more economically and environmentally suitable to producers.

Direct and indirect effect of factors suggest that cropping systems that are gaining interest from farmers, policy makers and society at large, lack the proper set up to assess ecosystem services.

Keywords: partial budget, cover crop benefits, cover crop viability

INTRODUCTION

Farmers are interested in the benefits of cover crops, but so far adoption of the practice has been limited in the region (Cai et al., 2019). By 2006 for example, only 18% of the farmers had used cover crops before and 11% had planted cover crops sometime in the preceding five years (Arbuckle & Roesch-McNally, 2015; Delgado & Gantzer, 2015); recently, however, the adoption of cover crops is reported to have increased to record highs (SARE-CTIC, 2020).

The profitability of a farm enterprise is affected by several factors, and more so with commodity products. With the push for sustainability efforts, cover cropping, one of many practices within a farm, stands alone when it comes to benefit-related issues. Profitability (the ability to generate revenue) of cover crops is affected by direct and indirect factors; the former includes species selection and management strategies while the latter refers to hidden benefits like the productivity of the following cash crop, enhanced soil health, reduced NO_3-N in the leachate, among others, mostly as a consequence of soil type and weather. Those hidden benefits are associated to cropping systems that are gaining interest from farmers, policy makers and society at large, which seem to lack the appropriate frameworks to evaluate and manage for agroecosystem services (Schipanski et al., 2014).

This is because measuring ecosystem services is complex; their assessment can be misleading due to the episodic nature of some services and the time sensitivity of management windows. For example, nutrient retention benefits occurs primarily during cover crop growth, weed suppression benefits occurs during cash crop growth through a cover crop legacy effect, and soil carbon benefits are accrued slowly over decades (Schipanski et al., 2014). We can see that ecosystem services are associated to time for gradual changes in the physical and biological cropping environment. As a result, and along with management, time is considered a component to cover crop profitability; in other words, outcomes from cover crops, whether positive or negative, are possible in the long-run (Bergtold et al., 2019); still, results might be associated to high degree of uncertainty. In the region, for example, the establishment of cover crops is highly risky due to the very short window opportunity, which often times offers below optimum conditions for growth (Rusch et al., 2020). In fact, the relatively small window of opportunity for seeding winter cover crops after corn is harvested and the additional labor, fuel, and seed expenses are reported as adoption constraints in the U.S. (Schipanski et al., 2014). Still, it is expected that the inclusion of cover crops will help promoting the long-term sustainability of farms, even if immediate net returns are not positive (Bergtold et al., 2019).

The objective of this study was to determine the profitability of overwintering and winterkilled cover crops early- and late-interseeded into corn. Trials and treatments were as described in chapters 2 and 3.

MATERIAL AND METHODS

Cover crop trials in corn-soybean rotation practices were conducted at multiple locations in Minnesota. Cover crop strategies included two grasses (annual ryegrass, AR; and cereal rye, CR), one legume (crimson clover, CC), one brassicae (forage radish, FR), a 2-way mixture of both grasses with crimson clover (ARCC and CRCC), and a 3-way mixture of both grasses with crimson clover and forage radish (ARCCFR and CRCCFR). Cereal overwinters while the others are winterkilled.

An AR-based (all winterkilled) cover crop trial conducted at Lamberton and Waseca was seeded at R5-R6 (late-interseeded) corn grown under different tillage practices. Two more trials, AR- and CR-based cover crops, were conducted at Grand Rapids, Lamberton, and Waseca; one trial was seeded at V4-V6 (early-interseeded) and the other at R5-R6 (late-interseeded) corn.

The profit potential of cover crops was analyzed using a partial budgets approach. For all locations, the control treatment (no cover, University recommended N rate) was considered as the current practice. Different combinations of cover crop strategies were considered as the potential alternatives/additions to the existing farm plan and analyzed separately.

Cover crop seed prices were based on the actual value paid from 2016 to 2019 (Table 8.1), and seeding cost was set at an average of $11.5/ac (www.threeriversagconsulting.com). Corn grain price was set at $0.06/lb, equivalent to an average price of 3.38/bu of the marketing years 2016 – 2019 in Minnesota (USDA-NASS, 2020c).

Table 8.1 Price of cover crops seed used in the economic analysis.

Cover crop	2016	2017	2018	2019	Average Price ($/lb)
Annual Ryegrass	0.66			0.95	0.81
Cereal Rye	0.27	0.43	0.25		0.32
Crimson Clover	1.20		1.20	1.09	1.16
Forage Radish	1.90				1.90

Cover crop seeding rate was based on different sources (SARE, 2020; extension.umn.edu, and extension.msstate.edu). Seeding rates were also adjusted for manual broadcast application under the canopy of primary crops, and prices were adjusted according to the 2- and 3-way mixtures rates (Table 8.2). Because cover crop use was the only management practice that changed compared to the treatment with no cover crop, our partial budgeting considered only costs and revenues that were changed due to the use of cover crops.

Table 8.2 Cover crops seeding rates (lb/acre) used in the study

Cover crop	**Monoculture**		**2-species mixture**		**3-species mixture**	
	AR	*CR*	*ARCC*	*CRCC*	*ARCCFR*	*CRCCFR*
Annual Ryegrass (AR)	25		12		12	
Cereal Rye (CR)		60		30		30
Crimson Clover (CC)			20	20	15	15
Forage Radish (FR)					9	9

Data for the economic analysis were organized into four categories, namely additional costs, reduced revenue, additional revenue and reduced costs. Additional costs refer to the costs that occur when there is a change in farm plan or practices but do not exist in the current farming system. Reduced revenue refers to the revenue currently being earned but that has been reduced after the adoption of the alternative plan/practice. Additional revenue includes the revenue received after the adoption of the alternative plan/practice but was not received under the existing farming system.

Reduced costs refer to those costs saved in existing farming system after the adoption of the alternative plan/practice (Rabin et al., 2007). If an alternative plan results in a positive value for the net change in profit, it indicates an increase in profit and if the value is negative, it indicates a decrease in profit. Due to lack of significance among cover crop treatments, results from the economic analysis area presented as pooled averages with ± one standard deviation.

RESULTS AND DISCUSSION

COVER CROPS AND TILLAGE PRACTICES

Corn grain yield was affected by year, tillage, year x location, year x tillage, and year x location x tillage interactions; neither location nor cover crop strategies affected grain yield (Chapter 2 \ study1). Therefore, the partial budget results are presented as pooled averages over cover crop strategies within a tillage practice for a given location. In all instances, cover crops use will result in a net loss ranging from as little as $30.6/ac to as much as $57.7/ac (Table 8.3).

Table 8.3 Average net change in profit ($/ac) from the use of winterkilled cover crops seeded late during three corn growing seasons at two locations in Minnesota.

Location	Tillage	2017	2018	2019
		Net profit ($/ac)		
Lamberton	Conventional-Till	-34.9 ± 13.4	-42.4 ± 8.6	-52.1 ± 11.2
	Strip-Till	-53.4 ± 22.7	-43.4 ± 23.5	-46.7 ± 21.7
	No-Till	-56.6 ± 15.4	-30.6 ± 30.8	-35.6 ± 15.2
Waseca	Conventional-Till	-55.3 ± 12.2	-49.0 ± 20.8	-39.0 ± 16.5
	Strip-Till	-46.3 ± 14.9	-49.2 ± 28.0	-57.7 ± 24.8
	No-Till	-53.6 ± 11.2	-49.7 ± 17.3	-31.7 ± 2.5

COVER CROPS AT MULTIPLE LOCATIONS

Corn biomass and grain yield from the late-interseeded cover crops study were both affected by location, year, and by the location x year interaction, but were not affected by cover crop strategy (Chapter 3 \ study1). Therefore, the partial budget results are presented as pooled averages over cover crop strategies within a given location. In all instances, cover crops use will result in a net loss ranging from as little as $31.5/ac to as much as $70.9/ac (Table 8.4).

Table 8.4 Average net change in profit ($/ac) from the use of a combination of overwintering (cereal rye) and winterkilled (crimson clover and forage radish) cover crops seeded late during two corn growing seasons at three locations in Minnesota.

Location	2017	2018
	Net profit ($/ac)	
Grand Rapids	-60.6 ± 21.9	-52.8 ± 57.1
Lamberton	-31.5 ± 27.4	-36.6 ± 24.7
Waseca	-52.7 ± 41.6	-70.9 ± 42.4

Similarly, biomass and grain yield of corn from the early-interseeded cover crops study were both affected by location, year, and by the location x year interaction, but no cover crop effect was observed (Chapter 3 \ study1). Therefore, the partial budget results are presented as pooled averages over cover crop strategies within a given location-year. In all instances, cover crops use will result in a net loss ranging from as little as $15.0/ac to as much as $53.8/ac (Table 8.5).

Table 8.5 Average net change in profit ($/ac) from the use of a combination of overwintering (cereal rye) and winterkilled (crimson clover and forage radish) cover crops seeded early during two corn growing seasons at three locations in Minnesota.

Location	**2017**	**2018**
	Net profit ($/ac)	
Grand Rapids	-35.6 ± 20.3	-38.8 ± 19.4
Lamberton	-15.0 ± 23.1	-34.0 ± 24.6
Waseca	-45.2 ± 19.4	-53.8 ± 60.9

It is important to highlight that in all instances (Table 8.3, Table 8.4, and Table 8.5) revenue loss was based on seed cost and the value of the grain yield reduction as compared to the no cover treatment. Potential benefits associated to ecosystem services were not considered because results were highly variable, suggesting that tangible outcomes might be beyond the timeframe of our study.

CONCLUSIONS

We determined the profitability of cover crops in corn-soybean rotation practices from results of trials conducted at multiple locations in Minnesota. Cover crop strategies included two grasses (annual ryegrass, AR; and cereal rye, CR), one legume (crimson clover, CC), one brassicae (forage radish, FR), a 2-way mixture of both grasses with crimson clover (ARCC and CRCC), and a 3-way mixture of both grasses with crimson clover and forage radish (ARCCFR and CRCCFR). Cereal overwinters while the others are winterkilled.

We found that none of the cover crop strategies used was economically viable. Our research suggested that early- and late-interseeded cover crops into corn could increase variable costs and reduce farm profits, at least in the short run.

It is important to note that our economic analysis neither considered the possibility of N credit nor the potential environmental benefits (including enhanced soil health, biodiversity, reduction of NO_3-N in the leachate, among others) from cover crops use. Moreover, the strategies evaluated in this project are just some of several others that should be investigated.

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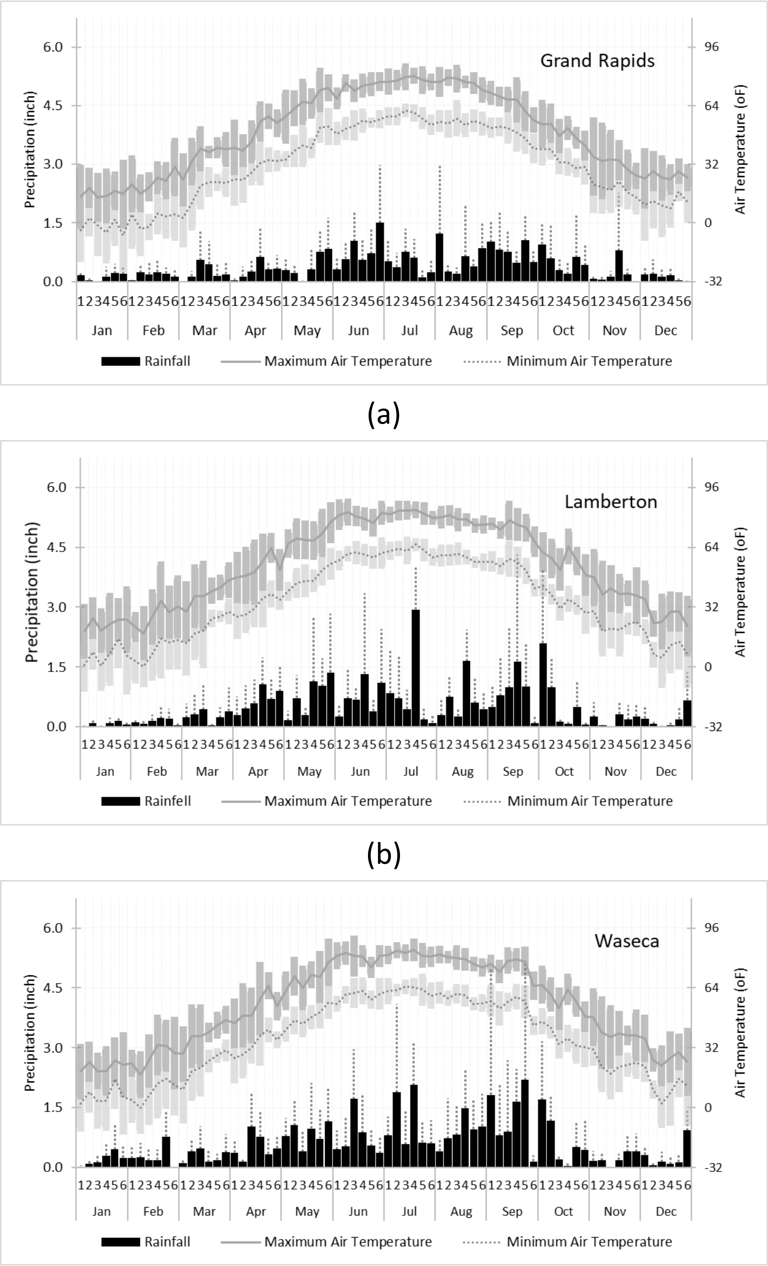
CHAPTER 9 – ANNEXES

ANNEX 1: WEATHER DATA



(a)

(b)

(c)

Figure 9.1 Average weather conditions during the experimental years. Values correspond to total rainfall and average air temperature within a 5-d period (pentad). Thick gray bars in air temperature and vertical dotted line in rainfall correspond to ± one standard deviation.

ANNEX 4: SOIL SOLUTION NO_3-N DATA

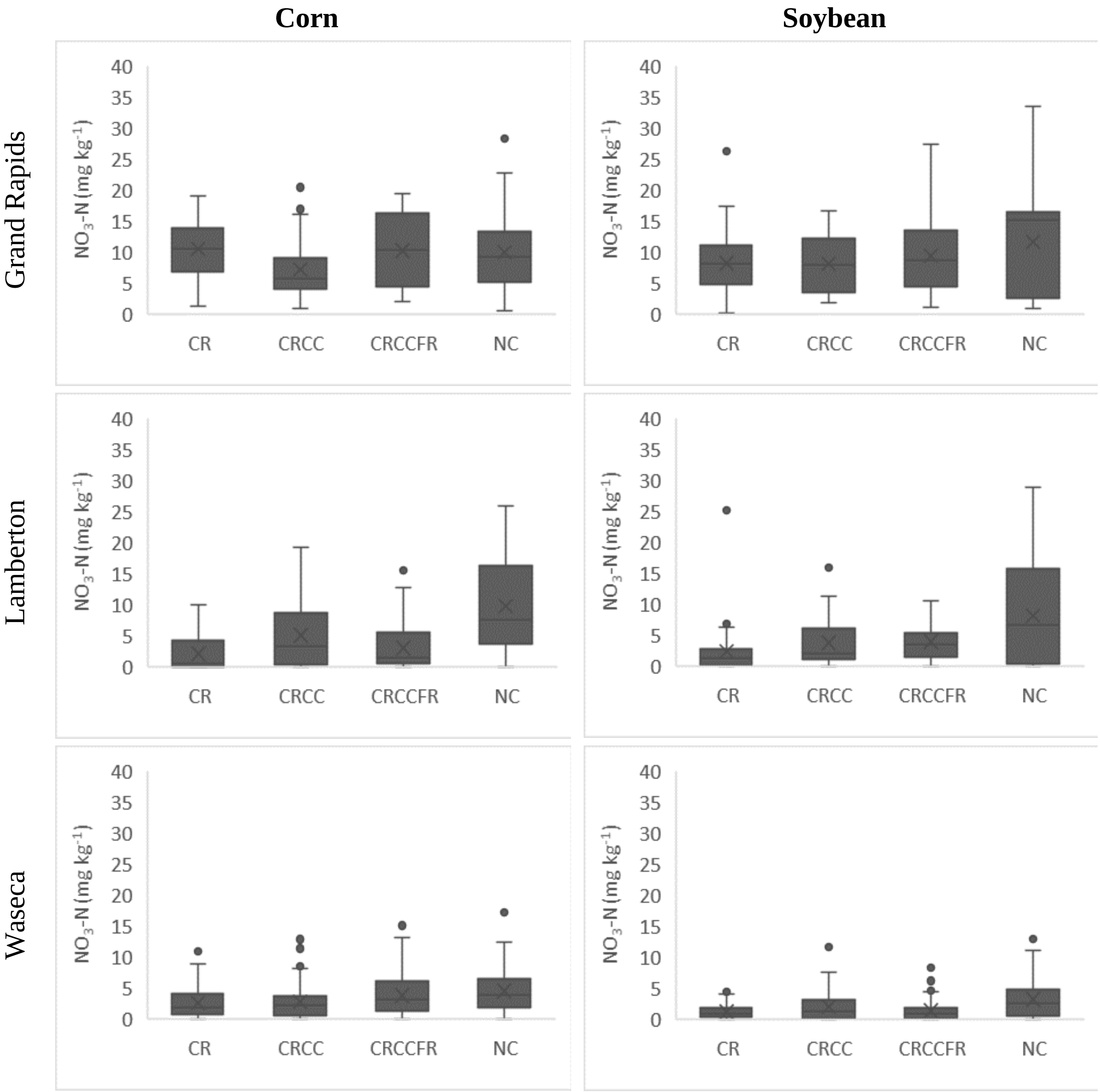


Figure 9.2 Effect of late interseeded cover crops on NO_3-N in the soil solution. Data were obtained with ceramic cups installed at 40 inches depth in corn and soybean plots from 2016 to 2018 at three locations in Minnesota.

ANNEX 5: PICTURES

Summer 2016. Study site at Lamberton (Aug)

Summer 2016. Ceramic cups at Lamberton (Aug)

Fall 2017. Cereal rye at Lamberton (Oct)

Fall 2017. CRCC at Lamberton (Oct)

Summer 2017. Study site at Grand Rapids (Aug)

Fall 2017. ARCCFR at Lamberton (Oct)

Fall 2017. AR at Lamberton (end Oct)

Fall 2017. ARCC at Lamberton (Oct)

Figure 9.3 Late-interseeded cover crops during different periods of growth at different locations in Minnesota

Fall 2016. ARCC at Lamberton (Aug)

Fall 2016. CRFR at Lamberton (Aug)

Summer 2016. CR at Waseca (Aug)

Summer 2016. CRCC at Lamberton (Aug)

Fall 2017. AR at Lamberton (Oct)

Fall 2017. CR at Lamberton (Oct)

Fall 2017. ARCCFR at Lamberton (Oct)

Fall 2017. CRCCFR at Lamberton (Oct)

Figure 9.4 Early-interseeded cover crops during different periods of growth at different locations in Minnesota

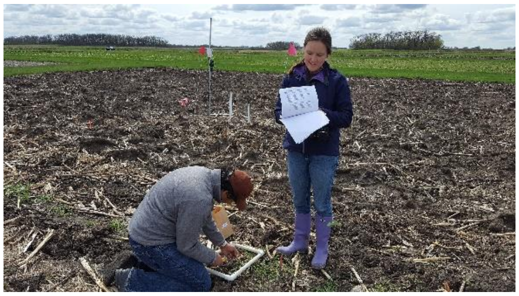
Spring 2017. Lamberton (May)

Spring 2017. Lamberton (May)

Figure 9.5 Installation of yellow sticky traps in the early-interseeded cover crops study. Lamberton, Minnesota

Spring 2017. Ceramic cups, CR at Lamberton (Mar)

Spring 2017. Collecting NO_3-N at Lamberton (Apr)



Spring 2017. Collecting biomass at Lamberton (Apr)

Summer 2018. Monitoring growth stages at Lamberton (Jun)

Figure 9.6 Data collection in the late-interseeded cover crop study. Lamberton, Minnesota

Summer 2017. ARCC at Lamberton (Sep)

End summer 2017. ARCCFR at Lamberton (Sep)

Spring 2018. Soil moisture, ceramic cups, and mineralization bags at Lamberton (Jun)

Summer 2018. Monitoring soil moisture at Lamberton (Jun)

Spring 2018. Biomass sampling at Lamberton (Jun)

Spring 2019. Buried bags for mineralization study at Lamberton (Jun)

Figure 9.7 Late-interseeded cover crops and tillage practices. Lamberton, Minnesota