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Implications of Broadleaf, Grass, and A Blend of Broadleaf And Grass Cover Crops on Soil Health and Corn Production in South Dakota

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IMPLICATIONS OF BROADLEAF, GRASS, AND A BLEND OF BROADLEAF AND GRASS COVER CROPS ON SOIL HEALTH AND CORN PRODUCTION IN SOUTH DAKOTA

BY

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THESIS ACCEPTANCE PAGE

Hunter Bielenberg

This thesis is approved as a creditable and independent investigation by a candidate for the master's degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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This thesis is dedicated to my parents for supporting me through everything.

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ABBREVIATIONS

C	carbon
EONR	economic optimum nitrogen rate
N	nitrogen
OM	organic matter
PMN	potentially mineralizable nitrogen
POXC	permanganate oxidizable carbon
TOC	total organic carbon

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ABSTRACT

IMPLICATIONS OF BROADLEAF, GRASS, AND A BLEND OF BROADLEAF AND GRASS COVER CROPS ON SOIL HEALTH AND CORN PRODUCTION IN SOUTH DAKOTA

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Cover crops have recently gained attention in the U.S. Midwest because of their potential to increase soil organic matter and protect overall soil health. This study was conducted to determine the effects of different cover crop mixtures on soil health measurements and corn grain yield at increasing nitrogen (N) rates. Cover crops were planted in the fall after small grains harvest as a dominantly grass mixture, dominantly broadleaf mixture, or a 50/50 grass and broadleaf mixture with a no cover crop control. Soil and cover crop biomass samples were collected in the fall before winter cold termination and in the spring before chemical termination of the cover crops. Soil samples were analyzed for permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration. Cover crop biomass samples were oven-dried and weighed to determine cover crop biomass. After spring cover crop termination, fertilizer-N was applied before planting corn at six rates: 0, 45, 90, 135, 200, and 225 kg ha^{-1}. The inclusion of cover crops did not improve soil health measurements with no statistical differences in soil health measurements among the different cover crop mixtures. However, there were differences among soil health measurements among site-years. Soil organic matter had a positive linear relationship with fall and spring POXC. The pH had a positive linear relationship with spring PMN and a negative linear

relationship with fall soil respiration. Precipitation had a positive linear relationship with fall soil respiration and a negative linear relationship with fall PMN. When including a cover crop compared to the control, there were no differences in corn grain yield at economic optimum N rate (EONR), EONR itself, and economic return 55%, 42%, and 52% of the time, respectively. The economic profit was reduced most often when planted under a blend cover crop (mean decrease = US\$235 ha^{-1}), then a grass cover crop (mean decrease = US\$265 ha^{-1}), and then a broadleaf cover crop (mean decrease = US\$296 ha^{-1}). The inclusion of cover crops did not improve soil health measurements compared to the no cover crop control. In the first year of comparing any species of cover crop mixture, growers should not expect to find differences among soil health measurements. However, a long-term trial to show the growing effects of cover crops is needed to fully compare these cover crop mixtures. In general, corn grain yield was not reduced by cover crop composition at EONR and did not change the amount of nitrogen needed for maximum corn grain yield. In conclusion, growers can plant cover crops regardless of composition in the fall after small grains harvest and terminate them in the spring before corn planting to maintain soil health without reducing corn grain yield at EONR or economic profit.

CHAPTER 1: INTRODUCTION

1.1 The Importance of Corn Production in South Dakota

Corn (*Zea mays L*) is an important cash crop in the United States and worldwide, producing food, feed, and fuel resources for the needs of a growing population. Corn is the highest producing grain in South Dakota (USDA, 2019). Of 17,500,000 ha of farmland in South Dakota, growers produce corn for grain production on 1,600,000 ha of that land (USDA, 2019). Since farmers have a limited amount of land to farm while needing economic profit, growers continually strive for the highest yield possible. The average corn grain yield in South Dakota is 9,700 kg ha^{-1} (USDA-NASS, 2019). In 2019, the South Dakota economy added $2,100,000,000 from these corn yields (USDA, 2019). South Dakota primarily uses the corn grain harvested for ethanol production and animal feed. It is also used for food products as well. Corn production has increased through intensive farming practices, which can reduce the quality of our soils. One practice that has shown the ability to improve the quality of our soils is the use of cover crops.

1.2 The Increasing Popularity of Cover Cropping Practices

Cover cropping is becoming more common throughout the U.S. Midwest. Growers base the type of cover crops grown on their perception of what a cover crop can do for their farm (Wang et al., 2019). The goals farmers may have can include controlling wind and water erosion to stop the degradation of their soil or to prevent and suppress problem weeds throughout their operation. Cover crops have had a 50% increase in the area grown from 2012 to 2017 in the United States (USDA, 2019; Zulauf and Brown, 2019). In South Dakota, from 2017 to 2019, cover crop usage has increased by 89% (Bly, 2020). In a separate survey in 2013, 13% of farmers felt their farm was planted with cover crops in South Dakota, while in 2018, 49% of South Dakota farmers considered themselves utilizing cover crops (Wang et al., 2019). Overall, cover crop usage has increased likely because of their ability to improve crop and soil resistance to adverse weather conditions and decrease problematic resistant weeds now being witnessed by the farmers who started planting cover crops early on (CTIC, 2017; Rorick and Kladivko, 2017; Wang, 2020). Word of mouth is also a significant factor. If one farmer has good or bad luck with cover crops, it has a higher chance of influencing if and how others will use them, affecting agroecosystem sustainability.

1.3 The Use of Cover Crops

Cover crops generally increase soil organic matter (OM) and overall soil health, which increases the beneficial microbial populations in the rhizosphere (Vukicevich et al., 2016; Morton and Abendroth, 2017; Rorick and Kladivko, 2017). Other reasons that growers adopt cover cropping practices is because compared to bare soil or winter fallow, cover crops reduce soil erosion, capture unused fertilizer nitrogen (N), decrease soil compaction, and suppress diseases and weeds (Nielsen et al., 2005; Snapp et al., 2005; Cherr et al., 2006; Tonitto et al., 2006; Gentry et al., 2013). Cover crops can make farming more resilient to stress, such as drought conditions or significant precipitation events. (Morton and Abendroth, 2017; Rorick and Kladivko, 2017). Cover crops are a reasonable soil degradation prevention tactic to help prevent soil, produce, and economic losses in the short term. There are also ways cover crops can help increase soil health, and scientists have been discovering new ways to measure and track the health of our soils.

There are various claims that cover crops can make farming more sustainable by improving soil health, but soil health is hard to define. The attempt to measure soil fertility and soil health is not a new concept to agriculture but has changed as we try to find more sustainable practices. Soil fertility measurements started with measurements of plant-available nutrients that were in the soil, and farmers would apply for the following cash crop (Borlaug, 1970; Vojvodic et al., 2014). With new measurements and synthetic fertilizer applications, mostly N manufactured through the Haber Bosch Process invented during the green revolution, crops were achieving higher yields than ever. (Cope and Evans, 1985). These same fertilizer manufacturing techniques from this era are still being utilized in modern agriculture today. Although crops are achieving higher yields than ever before, conservationists have realized that agriculture is still a wasteful and degrading process that needs to be further improved (Cassman et al., 2002; Ellis et al., 2013; Schipanski et al., 2014).

1.4 Analyzing Soil Health Concepts and Measurements

To further describe soil health measurements, we must first define the modern soil health definition. Soil health is defined as “the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans” (Al-Kaisi, 2014; Moebius-Clune et al., 2016; USDA-NRCS, 2016; Curell, 2018). Scientists tend to disagree on what measurements to use to determine soil health, but they do agree on several concepts of soil health, such as diversity. Diversity is beneficial for the ecosystem and the microbial populations in the ecosystem, a sign of soil health (Salon, 2013; Moebius-Clune et al., 2016). Studies have shown that when there are more cover crops grown, there is more organic carbon, which means that there is a probability of more soil microorganisms and more significant nutrient cycling because of these microorganisms (Sarrantonio and Gallandt, 2003; Wiedenhoeft and Cambardella, 2013; McDaniel et al., 2014; Schipanski et al., 2014). Scientists have started to measure soil health based on the number of microorganisms and how active they are. The general concept is that the more habitable the soil is for these microbes, the more habitable the soil will be for the crops growing there (Curell, 2018). A soil is supposed to act as a healthy growing medium for plant roots, regulate water, support plant and animal life, and aid in nutrient cycling (USDA-NRCS, 2016). Soil is living because it is teeming with microbes and other organisms living in it (Hill et al., 2000; Chu et al., 2019; Norris et al., 2020; USDA-NRCS, 2021). The soil microbes and plant roots alike thrive when the soil is a suitable and balanced environment. A precise and fast way to measure soil health is to measure how well soil microbes are living in the soil and base the overall health of the soil off that (Nielsen and Winding, 2002). Three common methodologies are permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration.

These methodologies were based highly on soil texture and microbial life associated with a particular soil texture (Moebius-Clune et al., 2016; USDA, 2019). A particular soil texture in the U.S. Northeast should have a particular soil health microbial reading according to the texture associated with it (Moebius-Clune et al., 2016; USDA, 2019). Although these methodologies worked very well in the U.S Northeast, they were later modified and improved to work outside of the U.S. Northeast and basing the measurements of POXC, PMN, and soil respiration off of if they are higher or lower in the same region (Moebius-Clune et al., 2016; USDA, 2019; Norris et al., 2020).

To achieve an overall, cost-effective understanding of the microbial biomass in the soil, a researcher may choose to complete a soil respiration test. The soil respiration test was advanced by Cornell University but is entirely related to other types of microbial respiration tests, including the Haney test, because laboratories measure soil microbial respiration in different ways in these tests (Chu et al., 2019). This particular soil respiration test uses a four-day incubation period to estimate the microbial biomass in the soil. Soil respiration can measure microbial biomass and population along with microbial activity (Moebius-Clune et al., 2016).

The Cornell Soil Health Institute adopted the POXC test as a soil health measure that is positively correlated with percent soil organic matter (OM) (Patrick, 1989; Gruver, 2015; Moebius-Clune et al., 2016). Permanganate oxidizable carbon is most simply described as the small fraction of organic carbon that is most readily available to soil microbes and will be their next labile carbon source for energy (Patrick, 1989; Moebius-Clune et al., 2016; Norris et al., 2020). The POXC test is a helpful soil health measure because it is strongly related to particulate OM, %OM, and microbial biomass carbon while also being relatively inexpensive to run (Skjemstad et al., 2006; Culman et al., 2012; Wiedenhoeft and Cambardella, 2013). Including cover crops in a crop rotation can provide higher amounts of OM needed as the food source for microbial communities (Sarrantonio and Gallandt, 2003; McDaniel et al., 2014; Schipanski et al., 2014).

Potentially mineralizable nitrogen measures the soil organic N fraction that is labile and can be used to estimate the N that can become plant available for the next growing season (Drinkwater et al., 1996; USDA NRCS, 2014; Clark et al., 2020). Since N is often a limiting nutrient for soil microbes to function, PMN measures how active the soil microbes could be because of how readily available N becomes for them to use (Drinkwater et al., 1996; USDA NRCS, 2014; Moebius-Clune et al., 2016; Spohn and Kuzyakov, 2013). When microbial populations become more abundant, nutrient cycling improves, which leads to a reduction of synthetic fertilizer and fewer nutrient losses. The PMN test can also be used as a strong indicator of how much N will be available in the soil for the next growing season through the decomposition and mineralization of organic N (Burger and Jackson, 2003; Moebius-Clune et al., 2016; Clark et al., 2019a, 2020; Norris et al., 2020). With these aspects in mind, PMN becomes critical to measure and understand because it is an indicator of N availability to crops (Moebius-Clune et al., 2016; Clark et al., 2019a; b, 2020).

1.5 Nitrogen Cycling and Fertilization

Nitrogen is often the most limiting nutrient for corn grain production (Gerwing and Gelderman, 2005). Nitrogen is needed in the most significant quantity of the soil-derived nutrients to build the critical components of protein (Weiss et al., 2009; Silva, 2017). In this way, corn grain production removes large amounts of N from the field, and this is why so much N fertilizer is needed (Weiss et al., 2009; Silva, 2017). To avoid excess N fertilizer applications, researchers have developed methods to estimate corn N fertilizer needs and reduce the chance of excess N fertilizer applications. The optimum fertilizer recommendation for N fertilization in South Dakota is 1.35 kg ha^{-1} multiplied by the corn grain yield goal minus the soil test nitrate-N level minus any legume credit (Gerwing and Gelderman, 2005). Adding the needed N to the system is effective but costly. The three main ways to add N to corn grain production are OM breakdown (mineralization), fertilization, and legume N fixation (Andraski and Bundy, 2002). In the conventional U.S. Midwest farming operation, the only time most cash crops are taking up nutrients is during the summer growing season. However, most of the N leaching occurs during the fall and spring when crops take up little to no water (Tonitto et al., 2006; Ruark and Franzen, 2020a).

One benefit of planting cover crops is that they can scavenge for and temporarily immobilize N by trapping it within the plant OM rather than leaching (Ruark and Franzen, 2020a). Human activity speeds up the N cycle with crop fertilization, which leads to excess nutrient loading (Aber et al., 2003; Berg, 2016; Alvarez et al., 2017). Too much nutrient loading can lead to nutrient losses (Tonitto et al., 2006). Immobilization of nutrients, including N, means they do not leave the agroecosystem and will be plant-available once mineralized. The length of time before N from cover crop residue is plant available depends on the C:N ratio of the cover crop residue (Ranells and Wagger, 1997). The lower the C:N ratio in the cover crop residue, the faster the soil microbes can mineralize it (Ranells and Wagger, 1997). We can improve the accuracy of N inputs by calculating possible N credits from different mixtures of cover crops and their residues they leave behind (Andraski and Bundy, 2002). N credit calculations from cover crop residue can reduce over-fertilization and reduce the amount of N that can potentially leach from the agroecosystem (Sarrantonio and Gallandt, 2003). Since broadleaf cover crops generally have lower C:N ratios, their residues will mineralize faster than grass cover crop residues and become plant available sooner, potentially decreasing the amount of N fertilizer needed to fertilize the corn crop. However, if a grass cover crop is planted, which usually has a higher C:N ratio than a broadleaf cover crop, it will take longer for microbes to mineralize N in the plant biomass. This N may not be available soon enough for the corn crop to use and potentially require more N fertilizer than if no cover crop were planted at all.

1.6 Cover Cropping Challenges

Some of the main challenges with the cover cropping system we see in the U.S. Midwest are management problems dealing with planting and termination. Many growers see planting cover crops as a toss-up to whether they will grow and get any benefit from them (Roesch-Mcnally et al., 2018). Cover crops struggle to germinate before winter frost in South Dakota because of its northern latitude. If germination and growth do not happen, the farmer receives no extra benefit from the cover crop they worked hard to plant after harvesting the cash crop (Roesch-Mcnally et al., 2018). On the other hand, the cover crop becomes an extra weed if the termination is not correctly executed (Weirich, 2017).

Cover crops also have the problem of adding a large amount of biomass to the soil surface. Although added biomass helps prevent soil erosion, it is also a soil insulator that inhibits the sun from warming the soil surface and delaying corn germination (Mirsky et al., 2013). Cover crops can cause early nutrient shortages as well. The main growth period for cover crops is during the springtime as the air and soil temperature get increasingly warmer, using the limited N and water resources. As the cover crop grows, it uses the fixed N and water resources available. Cover crops potentially deplete soil nutrients needed by cash crops by temporarily immobilizing soil N, which may cause yield drag during the following growing season (Justes et al., 2009). Cover crops not only temporarily leave fewer nutrients in the soil but also leave less water in the ground as well. Untilled fallow periods are usually a water building time, and cover crops use water, leading to water depletion during the cash crop growing period during a drier than average season (Blanco-Canqui et al., 2015; Alvarez et al., 2017).

1.7 Overcoming Cover Crop Challenges

Properly managing cover crops will help protect corn grain yield-limiting the potential adverse effects of cover crops mentioned in the previous section. Concerning germination problems, growers should plant cover crops as soon as possible after the cash crop harvest. After considering the germination of the cover crop, cash crop nutrient resources are the next concern. The nutrient makeup of varying cover crop mixtures is different, and residue decomposition is the main factor determining the rate nutrients taken up by the cover crop become available to the following cash crop (Brockmueller, 2020). Residue decomposition rate is positively correlated with the C:N ratio of the cover crop residue (Schmatz et al., 2017), which alters soil test nitrate-N levels during the growing season (Schmatz et al., 2017). Lower C:N ratio cover crop residues are cycled through microbes faster than higher C:N ratio residues (Martínez-garcía et al., 2018). Cover crop residues are the dead and decaying plant biomass added to the soil OM once they decompose. For the cover crop C:N ratios to not cause yield drag, soil nitrate-N tests should be done at representative points of a field during the same season every year, so adequate fertilization is still completed (Clay and Carlson, 2016). After managing the N rates that will be applied to the corn crop, water and environmental factors should be accounted for. Since cover crops do take up more than minimal amounts of water compared to winter fallow evaporation, growers should keep soil water data to ensure enough water for plant growth. Suppose soil is too dry or growers are expecting a drier than an average growing season. In that case, early termination of cover crops may help stop them from taking up too much water to avoid drought along with increasing early nutrient turnover (Alonso-Ayuso et al., 2014; Otte et al., 2019). These management practices together can help ensure a successful and sustainable cover cropping system.

1.8 Summary and Objectives

Corn grain is an essential resource to South Dakota and the United States economy. The use of cover crops can play a critical role in protecting and improving the soil to enable us to maintain and increase crop yields sustainably into the future. Early soil health measures were put into place to help production become more economically sustainable. However, because of farming intensification, a new model of soil health began to be developed. Because cover crops can play a part in these new soil health practices, they have started to become a widely integrated part of the crop production system in South Dakota. Cover crops have created various changes in how water and nutrients are cycled in the agroecosystem. With close management, though, growers can overcome these problems with germination, nutrients, and water limitations, and cover crops can start to play their part in improving soil health. Additionally, a better understanding of how cover crop mixtures with different C:N ratios influence soil health measurements and the subsequent effect of fertilizer-N applied, which will help growers optimize their economic return and minimize potential adverse environmental impact from spreading too much fertilizer-N.

The objectives of this research were to evaluate the effects of different cover crop mixtures planted after small grains on 1) soil health measurements and 2) corn production measurements, including economic optimal nitrogen rate, corn grain yield at economic optimal nitrogen rate, and economic profit.

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CHAPTER 2: GRASS, BROADLEAF, AND A BLEND OF GRASS AND BROADLEAF COVER CROP EFFECTS ON SOIL HEALTH MEASUREMENTS IN SOUTH DAKOTA

2.1 ABSTRACT

The evaluation of the influence of grass or broadleaf cover crops on soil health measurements is common in the U.S Midwest. However, the comparison among different cover crops that includes a blend of both grass and broadleaf species is limited. This study was conducted throughout central and eastern South Dakota for 11 site-years. Cover crops were planted in the fall after small grains harvest as a dominantly grass mixture, dominantly broadleaf mixture, or a 50/50 grass and broadleaf mixture along with a no cover crop control. Soil (0 to 15 cm depth) and plant surface residue samples were collected in the fall before winter kill and in the spring before chemical termination of any cover crops that may have grown back. Soil samples were analyzed for permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration. The inclusion of cover crops did not improve soil health measurements compared to the no cover crop control or among the different cover crop mixtures. However, there were differences among soil health measurements among site-years. Positive linear relationships were observed among fall POXC ($R = 0.18$) and spring POXC ($R = 0.44$) with percent soil organic matter, spring PMN with pH ($R = 0.63$), and fall soil respiration with fall precipitation ($R = 0.25$). In comparison, negative linear relationships were observed among fall soil respiration with pH ($R = -0.21$) and fall PMN with fall precipitation ($R = -0.52$). In the first year of planting broadleaf, grass, or a blend of cover crops, growers should not expect to find differences among soil health measurements. However, long-term trials are needed to determine whether, over time, differences in soil health among cover crops will develop.

Abbreviations: POXC, permanganate oxidizable carbon; PMN, potentially mineralizable nitrogen; OM, organic matter; N, nitrogen; TOC, total organic carbon; C, carbon; EC, electrical conductivity.

2.1 INTRODUCTION

In recent years cover crops have become more common in the U.S. Midwest (Zulauf and Brown, 2019; USDA-NASS, 2020). The increase in cover cropping practices is likely due to the benefits of planting cover crops. For example, planting cover crops increases crop and soil resistance to adverse weather conditions such as drought, hard rain events that cause erosion, and problematic weeds (CTIC, 2017; Rorick and Kladivko, 2017; Wang, 2020). Cover crops help with drought by increasing water infiltration rates when it does rain and against heavy rain events by acting as a canopy to protect the soil from water erosion. Cover crops act as a weed suppression mechanism by competing with weeds for resources. Soil organic matter building effects have also started being seen among fields with cover crops (Helgason et al., 2010; Blanco-Canqui and Jasa, 2019), along with resistance to wheel traffic compaction and improved aggregate stability (University of Maryland, 2015; Gruver et al., 2016). The United States, as a whole, has seen a 50% increase in the farmland planted with cover crops from 2012 to 2017 (USDA-NASS, 2019). Specifically, in South Dakota, from 2012 to 2017, cover crop use increased by 89% (Bly, 2020). These cover crops are essential for farming and environmental sustainability. Since there are many different species of suitable cover crops to grow, careful consideration must go into planning the best cover crop mixture to achieve on-farm goals.

Traditionally, growers have chosen to plant a single species cover crop to protect and improve the soil. These cover crops can be generally categorized into two main categories: broadleaf and grasses, which can protect the soil (CTIC, 2017; Rorick and Kladivko, 2017; Wang, 2020). Broadleaf species can be divided into two categories: brassicas and legumes. Brassica species, such as radishes and turnips, often have a taproot that can reduce compaction when the root expands and breaks up the plow pan better than the fibrous roots of cereal grass cover crops (Gruver et al., 2016; University of Massichutes, 2021). Legumes as cover crops can capture atmospheric N and convert it to a plant-available form (Parr et al., 2011; Gentry et al., 2013). This converted N is sometimes overproduced and available for subsequent crops, possibly reducing the need for N fertilizer applications (Herridge et al., 1990; Ranells and Wagger, 1996; Clark et al., 1997; Odhiambo and Bomke, 2001; Parr et al., 2011; Gentry et al., 2013; Alvarez et al., 2017; Yang et al., 2019). The low C:N ratios of the biomass from broadleaf cover crops is beneficial to soil microbial health because soil microbes tend to function better at lower C:N ratios (24:1) (Md Khudzari et al., 2016).

Grass cover crop species generally have a fibrous root system, are excellent nutrient scavengers, and leave a thick mulch after termination that can help build soil organic matter once broken down (Sullivan et al., 1991; Kaspar et al., 2007; Basche et al., 2016). Research has also shown that grass cover crops can improve soil aggregate stability and soil organic matter concentration (Blanco-Canqui and Jasa, 2019). Grass cover crops also increase water infiltration rates, decrease soil compaction through deep penetrating fibrous root systems (sorghum-sudangrass), and prevent soil erosion (University of Maryland, 2015).

Growing a multi-species blend of cover crops can be beneficial because it can help create an environment where the soil can benefit from both types of plants. An ideal cover crop mixture may be best if it can provide the services of building organic matter of grasses and the compaction reduction and soil feeding effects of broadleaf species (Sainju, 2009). One struggle farmers often encounter when growing cover crops is their ability to grow well, with weather patterns differing from year to year. Since the blend has multiple species of cover crops combined, it can help solve this problem because whichever species are most suitable for that year's weather conditions will flourish, even if the other species do not grow as well (Khan and McVay, 2019). However, further research is needed to better compare the effect of single-species grass and broadleaf cover crop mixtures to a blend on soil properties.

Including cover crops in a rotation can also influence soil health measurements (Appelgate et al., 2017; Blanco-Canqui and Jasa, 2019). Soil Health is defined as "the continued capacity of the soil to function as a vital living ecosystem that sustains plants, animals, and humans" (Moebius-Clune et al., 2016; Al-Kaisi, 2014; USDA-NRCS, 2016; Curell, 2018). Currently, there are many soil health aspects and no one definitive way to test the health of the soil or say precisely how healthy soil is (Moebius-Clune et al., 2016; Chu et al., 2019; Norris et al., 2020). However, soil health is commonly assessed by measuring different soil physical, chemical, and biological properties (Doran, 2002; Liu et al., 2007; Idowu et al., 2008). Commonly measured soil physical properties include soil aggregate stability (Amézketa, 1999), compaction, and water drainage (Lipiec and Hatano, 2003). Soil chemical aspects include electrical conductivity, reactive carbon, soil nitrate, soil pH, and extractable phosphorus and potassium (Schoenholtz et al., 2000; USDA-NRCS, 2021). Soil biological measurements include root pathogen pressure assessment, beneficial nematode population, parasitic nematode population, and the weed seed bank assessment (Moebius-Clune et al., 2016). The soil health measurements we choose to focus on in this study were the permanganate oxidizable carbon (POXC) test, potentially mineralizable nitrogen (PMN) test, and the soil respiration test. These tests help us understand how carbon and nitrogen cycle through the agroecosystem, have been shown to show changes faster due to changes in management practices, and are relatively inexpensive to run (Culman et al., 2012; Aislabie and Deslippe, 2013; Hurisso et al., 2016; Moebius-Clune et al., 2016; Chu et al., 2019; Norris et al., 2020).

The inclusion of broadleaf cover crops can influence the soil health measurements of POXC, PMN, and soil respiration. Including radishes (*Raphanus sativus*) as cover crops increased POXC to total organic carbon (TOC) ratio compared to plots that did not have cover crops (Wang et al., 2017a). The C:N ratio of the cover crop, previous cash crop residue, and the C:N ratio of the soil have been reported to increase the PMN (Sanchez et al., 2001; Schomberg et al., 2006; Snapp and Surapur, 2018). It was speculated that these effects occurred because cover crops with typically lower C:N ratios (e.g., broadleaf cover crops) will have higher PMN because soil microorganisms decompose lower C:N ratio plant residues (hairy vetch cover crop, 25:1) more readily than high C:N plant residues (rye straw, 82:1) (Schomberg et al., 2006; Usda, 2011). Regarding soil respiration, one study completed in a Mediterranean environment showed that rape (Brassica napus) cover crops had higher soil respiration rates when compared to a no cover crop control (Sanz-Cobena et al., 2014).

Grass cover crops have also affected the soil health measurements of POXC, PMN, and soil respiration. Wiedenhoeft and Cambardella (2013) used cereal rye (*Secale cereale*) as a cover crop, which showed an increase in particulate organic matter (POM) after a soybean-corn silage rotation compared to the no cover crop control. In two studies, cereal rye as a cover crop also increased PMN when planted after soybean or corn silage crops (Wiedenhoeft and Cambardella, 2013; Norris and Thomason, 2018). Further, a study in a Mediterranean environment showed that barley (Hordeum vulgare) cover crops enhanced soil respiration rates compared to the no cover crop control (Sanz-Cobena et al., 2014).

As stated earlier, planting grass and broadleaf blend as a cover crop is likely an excellent option to gain the soil benefits associated with grass and broadleaf cover crops. Grass and broadleaf blends have been shown to be more productive than a single species cover crop (Khan and McVay, 2019). One study found that there was consistently greater biomass in a hairy vetch and cereal rye biculture cover crop mixture than vetch only or rye only cover crop mixture, potentially increasing percent OM in the grass and broadleaf blend (Sainju et al., 2005). However, a limited number of studies compare the effect of multi-species blends of cover crops to single grass and broadleaf cover crops on soil health measurements. Therefore, this research's objectives were to determine the effect of grass and broadleaf (single and mixed species) cover crops compared to a no cover crop control on surface residue and soil health measurements.

2.2 MATERIALS AND METHODS

2.2.1 Experimental Design

This study was conducted in eastern and central South Dakota from the fall of 2017 to the fall of 2020 on 11 site-years. The research sites are listed by geographic location, coordinate points, and soil classification in table 2-1. The experiment was conducted as a randomized complete block design with four treatments replicated four times. The four cover crop treatments were: 1) dominantly grass mixture, 2) dominantly broadleaf mixture, 3) a 50/50 blend of grass and broadleaf species, and 4) a control (no cover crop). Each cover crop plot size was 7.5 m in length and 4.5 m in width. The dominantly grass mixture included 22.5% oats (*Avena Sativa*), 22.5% barley (*Hordeum vulgare*), 22.5% foxtail millet (*Setaria italica*), 22.5% sorghum-sudan grass (*Sorghum x drummondii*), 2.5% radish (*Raphanus sativus*), 2.5% turnip (*Brassica rapa subsp. Rapa*), 2.5% pea (*Pisum sativum*), and 2.5% lentil (*Lens culinaris*). The dominantly broadleaf mixture included 2.5% oats, 2.5% barley, 2.5% foxtail millet, 2.5% sorghum-sudan grass, 22.5% radish, 22.5% turnip, 22.5% pea, and 22.5% lentil. The 50/50 blend mixture included 12.5% of all the previously mention cultivars resulting in an equal amount of grasses and broadleaf species planted. Cover crops were planted using a no-till drill after the fall harvest of winter wheat (Salem 2018, Salem 2019, Beresford 2018, and Beresford 2019 were oats) between early to mid-August. The cover crops were either cold terminated during the winter months or chemically terminated with 3229 mL ha^{-1} of glyphosate in the spring 1 wk before planting.

2.2.3 Sampling and Analysis

Cover crops and previous crop residue samples were collected within two 30.5 cm^2 areas from each treatment in the fall before cover crop winter kill and in the spring before chemical termination of any surviving cover crops before corn planting. Fall sampling dates occurred between late September and early November, and spring sampling took place during May. The surface residue samples included previous crop and cover crop residue to get an overall idea of how cover crops can affect the biomass of the previous crop residue.

Soil samples were obtained at the same time as the cover crop and previous crop residue collection to assess different cover crop mixtures' influence on soil health measurements. Twelve soil samples were collected from each replication of each cover crop treatment from a depth of 0 to 15 and 15 to 30 cm using a soil probe with an inside diameter of 1.9 cm. Soil samples were air-dried and ground to pass through a 2 mm sieve. These soil samples were analyzed for general soil fertility measurements (NO_3-N 0-15 cm and 15-60 cm, Olsen P, potassium, OM content, and pH tests) following the recommended chemical soil test procedures for the North Central Region (NCR221, 2015) (Table 2-2). Only soil NO_3–N was analyzed at the 0 to 15 and 15 to 30 cm depths. All others were only analyzed using the 0 to 15 cm depth.

The three tests for soil health were permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration. The permanganate oxidizable carbon test was done using the protocol adopted by the Cornell Soil Health Laboratory 2016 methods and is the same as implementing the active carbon test from Weil et al. (2003) with minor changes as in Culman et al. (2012). For instance, 2.5 g of air-dried soil was placed into plastic centrifuge tubes, and 2.0 ml of 0.2M $KMnO_4$ was added to the soil. Next, 18.0 mL of deionized water was added to the soil and put on a rotary shaker at high speed for two minutes. After shaking, the soil settled for 10 minutes. Using a pipette, 0.5 mL of the supernatant was transferred into a 50 mL plastic centrifuge tube containing 49.5 mL of deionized water. Finally, the supernatant absorbance was read directly in this centrifuge tube using a Brinkman PC 800 colorimeter spectrophotometer at 550 nm. Four standard concentrations of 0.005, 0.01, 0.015, and 0.02 M $KMnO_4$ with two controls and blanks were also used. The POXC measurement was then calculated using the intercept of the standard curves created with the standard concentration test tubes to get the total POXC concentration.

The potentially mineralizable nitrogen test was done using the protocol adopted for the Cornell Soil Health Laboratory 2016 methods based on Drinkwater et al. (1996), while the microplate assay for colorimetric ammonium determination protocol was from Rhine et al. (1998). Two replicates were measured out, in which one had a zero-day incubation period, and the other was incubated for seven days. In the one-day replicate, eight grams of air-dried soil was measured into a plastic centrifuge tube, and 40 mL of 2.0 M KCl solution was pipetted into the plastic centrifuge tube. Next, these samples were placed on the rotary shaker for one hour and centrifuged for 10 minutes at 1500 RPMs. Finally, approximately 20 mL of the extract was poured through round filter paper into tubes. The seven-day incubation replicates were completed by adding 10 mL of deionized water to the soil in a plastic centrifuge tube and incubated at 37° C for seven days. Next, 30 mL of deionized water was added, and the exact steps from the one-day replicates were followed to extract ammonium-N. For ammonium-N determination, 50 µL of the soil extract was pipetted into 96 deep well microplates in replications of three deep wells per soil sample extract. Then, 50 µL of the citrate reagent was added and allowed to react for at least one minute. Next, 50 µL of the PPS-nitroprusside reagent was added to the wells. Finally, 25 µL of the buffered hypochlorite reagent was added to each of the wells. When it was time for the solution to start reacting, 100 µL of deionized water was added to each of the wells, covered with a thin plastic film, vortexed with a Thermo Scientific high-speed vortex, and let sit for 45 minutes undisturbed to complete color development. Two blank, and 0, 2, 5, 10, 25, and 50 ppm NH_4-N L^{-1} concentration standards were also prepared for comparison. After the 45-min. incubation period was complete, the micro assays were read with a Biotek Epoch spectrophotometer at 660 nm absorbance level. The PMN measurement was then calculated by subtracting the zero-day measurement from the seven-day measurement.

The soil respiration test was done using the protocol adopted by the Cornell Soil Health Laboratory 2016 measurement based on Zibilske (1994). Two round filter papers were put into the bottom of a wide mouth mason jar with a small, perforated aluminum tray on the top of those filter papers. Twenty grams of air-dried soil was measured out onto the aluminum trays. A trap assembly was installed using a pizza stand with a 10 mL beaker filled with 9 mL of 0.5 MOL KOH solution taped onto the pizza stand with double-sided cellulose tape. Then, 7.5 mL of deionized water was dispensed down the side of the jar to the bottom of the aluminum tray to soak the filter papers in the bottom and rewet the soil. The lid of the jar was closed and incubated for four days undisturbed. Original KOH EC was measured to obtain an initial reading before CO_2 addition could lower the EC of the solution. A blank jar, with no soil, was prepared to calculate the amount of CO_2 in the air of the jar. After four days of incubation were complete, the EC of the KOH solution was measured using a Mittler Toledo Seven Excellence Multiparameter EC meter probe. The soil respiration measurement was then calculated, comparing the used KOH EC measurement from the jar against the new KOH solution and the blank jar with no soil. The drop in EC determined the amount of CO_2 respired by the microbes in the soil sample.

2.2.6 Statistical Analysis

The effects of cover crop treatments on POXC, PMN, and soil respiration were analyzed with RStudio statistical software version 3.6.1 and interpreted using a two-way ANOVA and a linear model for all independent variables (R Core Team, 2019). A randomized complete block design was used as the experimental design with four replications in each block. Site-year, cover crop treatment, and their interaction was considered a fixed-effect, while block within each site-year was considered a random effect. Normality and constant variance assumptions were tested and shown to be met using the Shapiro-Wilk normality test and examining the residuals plots using the ggResidpanel package within R statistical software (Goode and Rey, 2019). Differences among soil health measurements caused by cover crop treatment and site-year were determined using Fishers Least Significant Difference at $p < 0.05$ significance level for mean separation using the agricolae package (Felipe de Mendiburu, 2017) within R statistical software. Differences among means were declared significant at $P < 0.05$. Site-years were analyzed separately when there was a site-year × cover crop treatment interaction. Potentially mineralizable nitrogen in the fall and spring as well as soil respiration in the spring were evaluated at only ten site-years due to insufficient amounts of soil to run the test in one site-year. Soil surface residue was only assessed at ten site-years in the fall and nine site-years in the spring due to missing samples. When only site-year had a significant effect on soil health measurements, the correlation between soil characteristics and weather conditions among soil health measurements was completed using Pearson's product-moment correlation in R.

2.3 RESULTS AND DISCUSSION

2.3.1 Weather

Cover crops were planted between mid-August and early September after small grains harvest, and corn was planted in early May of the following year. Weather was recorded using South Dakota Mesonet. The average monthly temperatures of this period ranged from -14.2 to 21.0 °C (Figure 2-1). The monthly average temperature departure from normal varied among site-years, but most site-years were within 2°C of normal. The only exception was the month of February, when temperatures at Pierre 2020, Blunt 2020, Mitchell 2020, and Henry 2020 dropped below average by 5°C (Figure 2-2). Temperatures that terminated grass cover crops (-6°C) and broadleaf cover crops (-1°C) occurred between mid-November to early December each year (Figure 2-1). Monthly precipitation during the cover crop growing period ranged from 0 to 171.5 mm (Figure 2-3). Generally, precipitation during the fall was greater than normal (>50mm above average), while in the spring, it was within 20 mm of normal (Figure 2-4). However, the precipitation levels for Salem 2019 were about 50 mm above average during March through May. The highest monthly precipitation occurred in September at Mitchell 2020 (+112.8 mm mean deviation) (Figure 2-1). Overall, precipitation at each site-year was adequate to sustain cover crop growth (Barnard et al., 2015).

2.3.2 Biomass of Surface Residues

Both cover crop residue (living and dead) and previous crop residue was collected for surface residue biomass samples in the fall before winter kill and in the spring one week before planting corn. Therefore, both the no cover crop and cover crop treatments had biomass collected (Table 2-4). This method was used because growing cover crops can speed up the previous crop residue decomposition, reducing the amount remaining in the field (Brockmueller, 2020). A high surface residue value in the control could mean little decomposition occurred, whereas a lower value implies greater decomposition of the previous cash crop residue.

Varying weather patterns (Figure 2-1) across site-years likely caused the wide range of fall (652 to 8349 kg ha^{-1}) and spring (953 to 5204 kg ha^{-1}) surface residue amounts (Table 2-3). Other studies with similar cover crop planting dates accumulated between 210 to 1990 kg ha^{-1} in IA (Wiedenhoeft and Cambardella, 2013) and 4413 to 12096 kg ha^{-1} in central IL (Boydston and Williams, 2017), which on average were similar to our findings. Maximum cover crop biomass was greater in IL than our study, which may be due to their warmer temperatures and longer cover crop growing season as their cover crop would have been winter-killed sometime in December instead of November.

Cover crops for this study were planted between mid-August and early September after small grain harvest, which can be different for other parts of the U.S. Midwest. Since small grains are harvested in the late summer and early fall, there is a more extended cover crop growing season when compared to a corn and soybean rotation, which are harvested mid to late fall. In the drier, southern regions of the U.S. Midwest, such as NE and KS, small grains harvest occurs earlier than in SD (U.S. Department of Agriculture, 1997). Therefore, cover crop planting occurs earlier in these regions, increasing the growing season length and likely leading to greater cover crop biomass before winter kill of cover crops occurs.

The effect of including cover crops and their composition on fall and spring surface residue biomass was influenced by the site-year × cover crop interaction (Table 2-3). In the fall, planting cover crops regardless of composition did not affect surface residue biomass in seven of the ten site-years (70%) sampled (Table 2-4). In the three site-years where cover crops influenced fall surface residue, two site-years had greater fall surface residue in one or more of the cover crop treatments than the control. On the other site-year, fall surface residue from one or more cover crops was greater than the control. Specifically, fall surface residue in Plankinton 2020 was greater with a broadleaf cover crop (8348 kg ha^{-1}) than grass (5569 kg ha^{-1}) and the control (5548 kg ha^{-1}), but the grass and control were similar. Whereas in Salem 2018, all cover crop mixtures (mean = 4020 kg ha^{-1}) had greater surface residue than the control (1667 kg ha^{-1}). In contrast to these results, in Garretson 2018, the control had the greatest fall surface residue (5281 kg ha^{-1}), and the blend had the least (3792 kg ha^{-1}), with the grass and broadleaf being similar to all treatments.

Including cover crops likely did not increase surface residue in most site-years compared to the control because including cover crops may have increased decomposition rates of the previous cash crop surface residue, resulting in similar total surface residue values. Evidence for this occurred at Garretson 2018, Beresford 2020, Mitchell 2020, and Blunt 2020, where the surface residue values of the controls were all numerically or significantly greater than where cover crops were planted. A study in southeastern SD demonstrated this possibility where they reported less previous crop residue where cover crops were growing (Brockmueller, 2020). Therefore, growing cover crops can potentially increase the previous crop residue decomposition, reducing previous crop residue and potentially increasing available nutrients for the succeeding cash crops. Overall, including cover crops regardless of the mixture in a small grain-corn rotation does not consistently affect fall surface residue. However, when cover crops do influence fall surface residue, there is no consistent difference among cover crop mixtures. These results differ from a study in Urbana, IL, on a silty loam soil and in eastern NE on a silty clay loam soil where a grass cover crop produced greater biomass than a broadleaf cover crop (Boydston and Williams, 2017; Blanco-Canqui and Jasa, 2019). These differences may be because their studies only weighed and compared cover crop residue and did not include previous crop residue. In future studies, it would be beneficial to partition the grass and broadleaf cover crops along with previous crop residue to better understand the influence of growing cover crops on the decomposition of previous crop residues.

In the spring, planting cover crops regardless of composition did not affect surface residue biomass in seven of the nine site-years (78%) sampled (Table 2-4). The control had less than or equal to spring surface residue in the two site-years where cover crops influenced spring surface residue compared to all other cover crop treatments. Specifically, spring surface residue in Salem 2018 was greater with all cover crop mixtures (mean = 4150 kg ha^{-1}) than the control (2661 kg ha^{-1}). Whereas in Pierre 2020, the control (1591 kg ha^{-1}) was less than the blend (2142 kg ha^{-1}), but the grass and broadleaf cover crops were similar to all other treatments. These results indicate that the effects of cover crops on surface residue were similar regardless of the fall or spring sampling time.

2.3.3 Soil Health Measurements

The soil health measurements that were evaluated in these cover crop field trials were POXC, PMN, and soil respiration. In the first year of comparing cover crop mixtures, regardless of cover crop composition, cover crops did not affect soil health measurements within the site-year × cover crop interaction or the main effect of cover crop (Table 2-3). These results indicate that in the first year of comparing grass, broadleaf, and a blend of grass and broadleaf cover crops, cover crops did not significantly affect soil health measurements. However, other studies did find differences in soil health measurements in the first year of including a cover crop. In a continuous corn silage rotation on US coastal plain soils, including radishes as a cover crop, increased POXC and TOC after the first year (Wang et al., 2017b). In a soybean-corn silage rotation in central IA, including ryegrass as the cover crop increased POXC after the first year (Wiedenhoeft and Cambardella, 2013).

Effects of including cover crops on soil health measurements have shown inconsistencies in short-term studies (<7 years). In contrast, a long-term study (30 years) with cover crop blends of peas and soybeans for broadleaf species and cereal rye and grain sorghum as grass species reported cover crops consistently increased physical soil health measurements (Blanco-Canqui and Jasa, 2019). Similar results to our study were found with PMN in a trial completed by Wiedenhoeft and Cambardella (2013). They found PMN to be similar during the first year of planting a rye cover crop after soybeans. Still, results after the second year of corn silage indicate that the rye cover crop treatment increased in PMN compared to the no cover crop control (38% higher) (Hendrix et al., 1988; Wiedenhoeft and Cambardella, 2013; Sanz-Cobena et al., 2014; Turrini et al., 2017; Schmidt et al., 2018). Hendrix et al. (1988b) found that the planting of a clover cover crop had greater soil respiration than when compared to planting a rye cover crop. Sanz-Cobena et al. (2014) found that the planting of barley and hairy vetch cover crop had greater soil respiration than a rape cover crop. Turrini et al. (2017) found that soils under permanent long-term green cover crops during olive production increases soil respiration. Schmidt et al. (2018) also found that the long-term use of cover crops increased microbial communities in the soil and soil respiration compared to no cover crops. These results indicate that improving soil health measurements may take a more extended period than just the first year of implementation to have a consistent, measurable effect.

Including a cover crop did not affect soil health measurements, but site-year significantly influenced each soil health measurement (Table 2-3). Soil health measurements were related to OM, pH, and precipitation during the month before sampling and temperature during the month of sampling (Table 2-6). Positive linear relationships among site-specific soil properties and weather variables included pH with spring PMN (R = 0.63), percent soil OM with fall POXC (R = 0.18), and spring POXC (R = 0.44), and precipitation with fall soil respiration (R = 0.25). Negative linear relationships included both pH with fall soil respiration (R = -0.21) and precipitation with fall PMN (R = -0.52). These relationships between the different soil properties and weather variables across site-years are likely what resulted in the significant effect of site-year on soil health measurements. Other studies determined that OM was positively correlated with POXC (Hurisso et al., 2016; Norris et al., 2020), pH was negatively related to PMN and positively related to soil respiration (Turner, 2010; Malik et al., 2018; Norris et al., 2020). In our study, precipitation was positively related to PMN, which was opposite of what other studies found (Zhou et al., 2009; Engelhardt et al., 2018; Clark et al., 2020). These results indicate that there is a relationship between soil characteristics and weather patterns with soil health measurements.

2.4 Conclusions

After the first year of including a broadleaf, grass, and a grass/broadleaf blend during this three-year study of cover crops on South Dakota soils, there were limited effects on changing surface residue and soil health measurements compared among each other and the no cover crop control. The fact that planting cover crops regardless of composition did not affect fall or spring surface residue biomass in 7 of the 11 site-years suggests that growing cover crops may have accelerated old cash crop decomposition. This accelerated decomposition can help build soil OM and improve nutrient cycling over time. In future studies, previous cash crop residues should be partitioned from fresh cover crop biomass to precisely observe how much they add to the total surface residue.

Overall, a longer-term comparison of cover crop mixtures (single and multiple species) on soil health measurements is needed to determine if and when differences begin to occur. To better understand how these plant species interact with each other in the cover crop mixtures, implementing several treatments of single species cover crop treatments would be beneficial for referencing.

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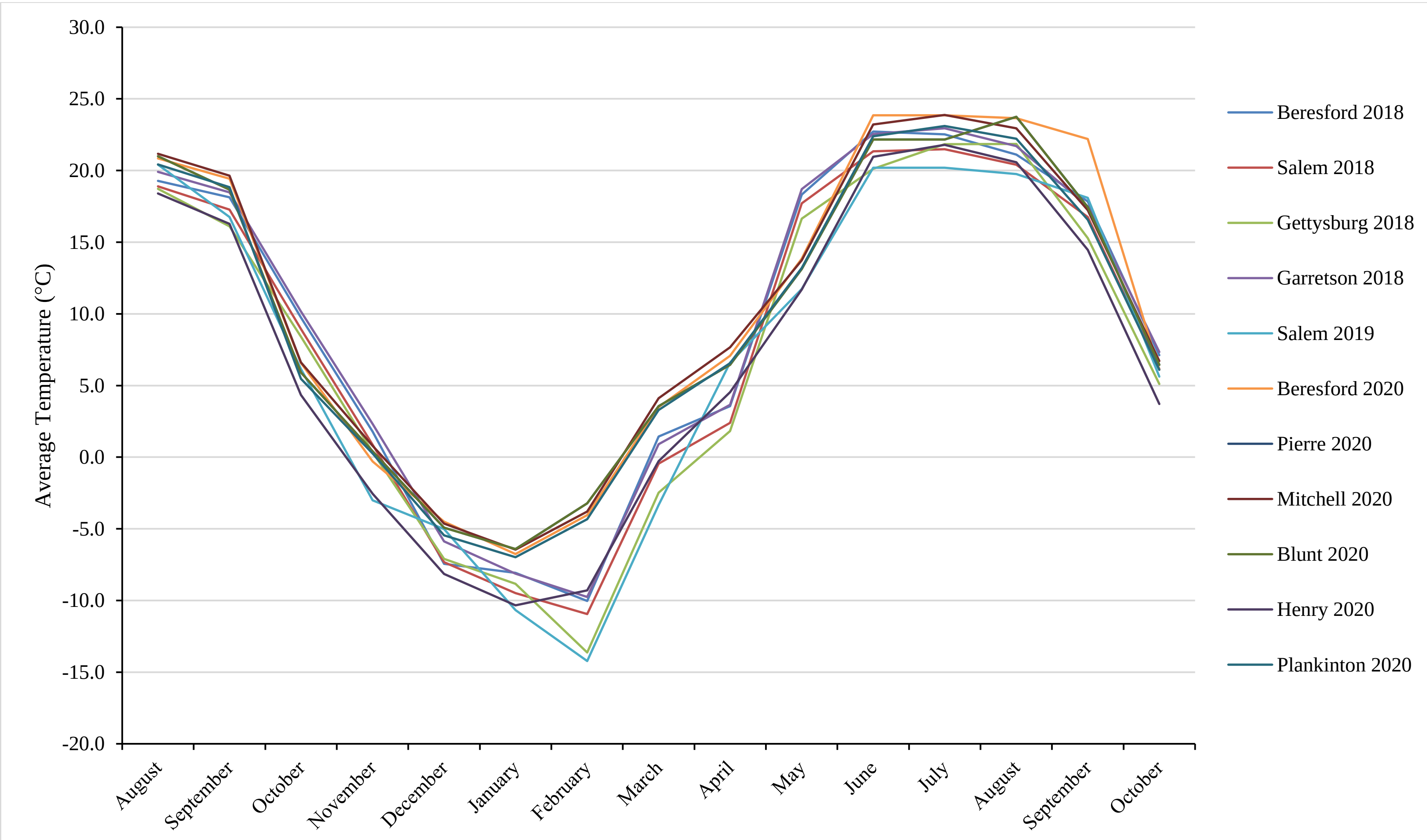

Figure 2-1. Monthly average temperatures (°C) at all site-years throughout South Dakota from August when the cover crop was seeded to October of the following year after corn grain harvest.

Figure 2-2. Monthly average temperature departures (°C) from the 30-year average (1981–2010) at all site-years throughout South Dakota from August when the cover crop was seeded to October of the following year after corn grain harvest.

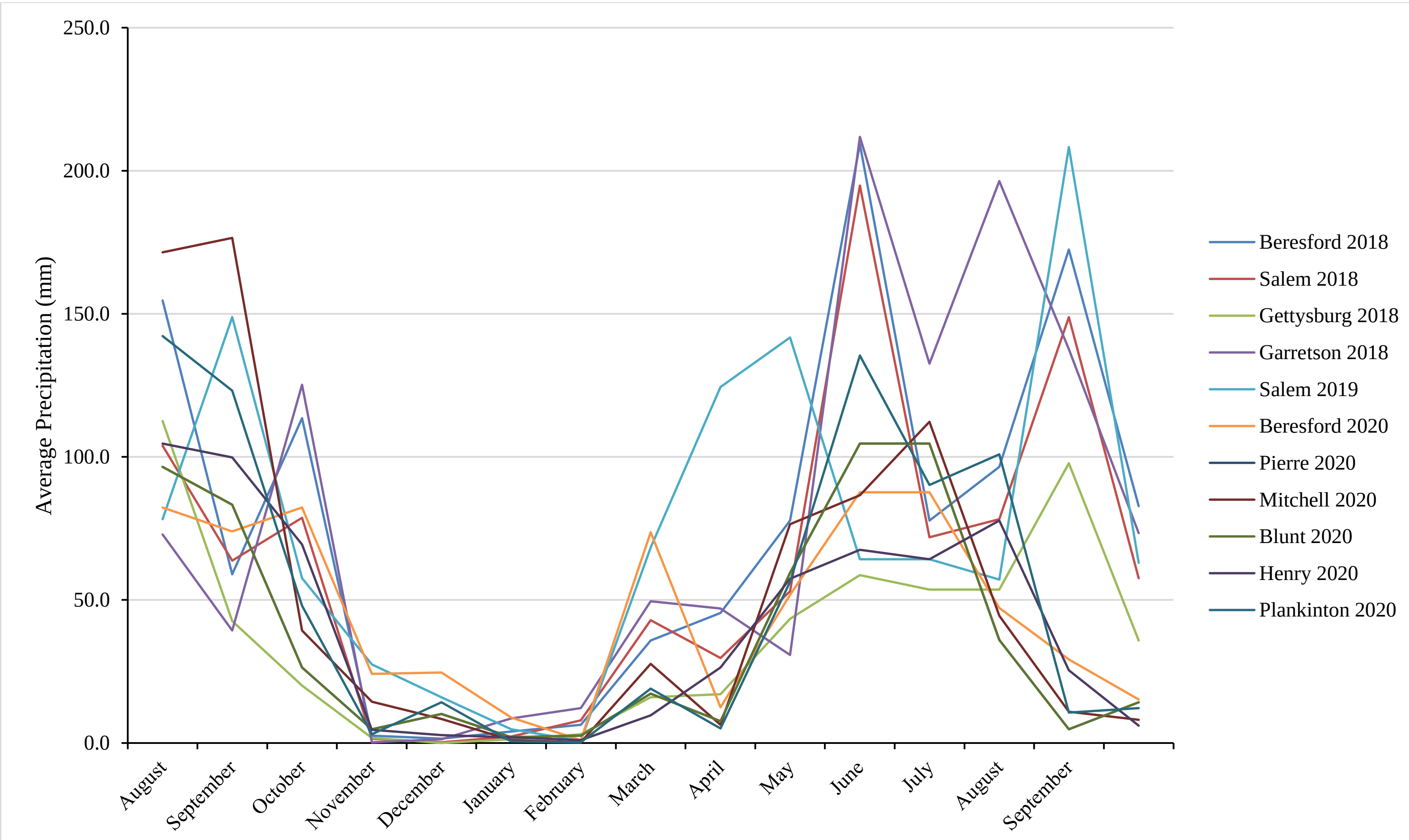

Figure 2-3. Monthly average total monthly precipitation (mm) at all site-years throughout South Dakota from August when the cover crop was seeded to October of the following year after corn grain harvest.

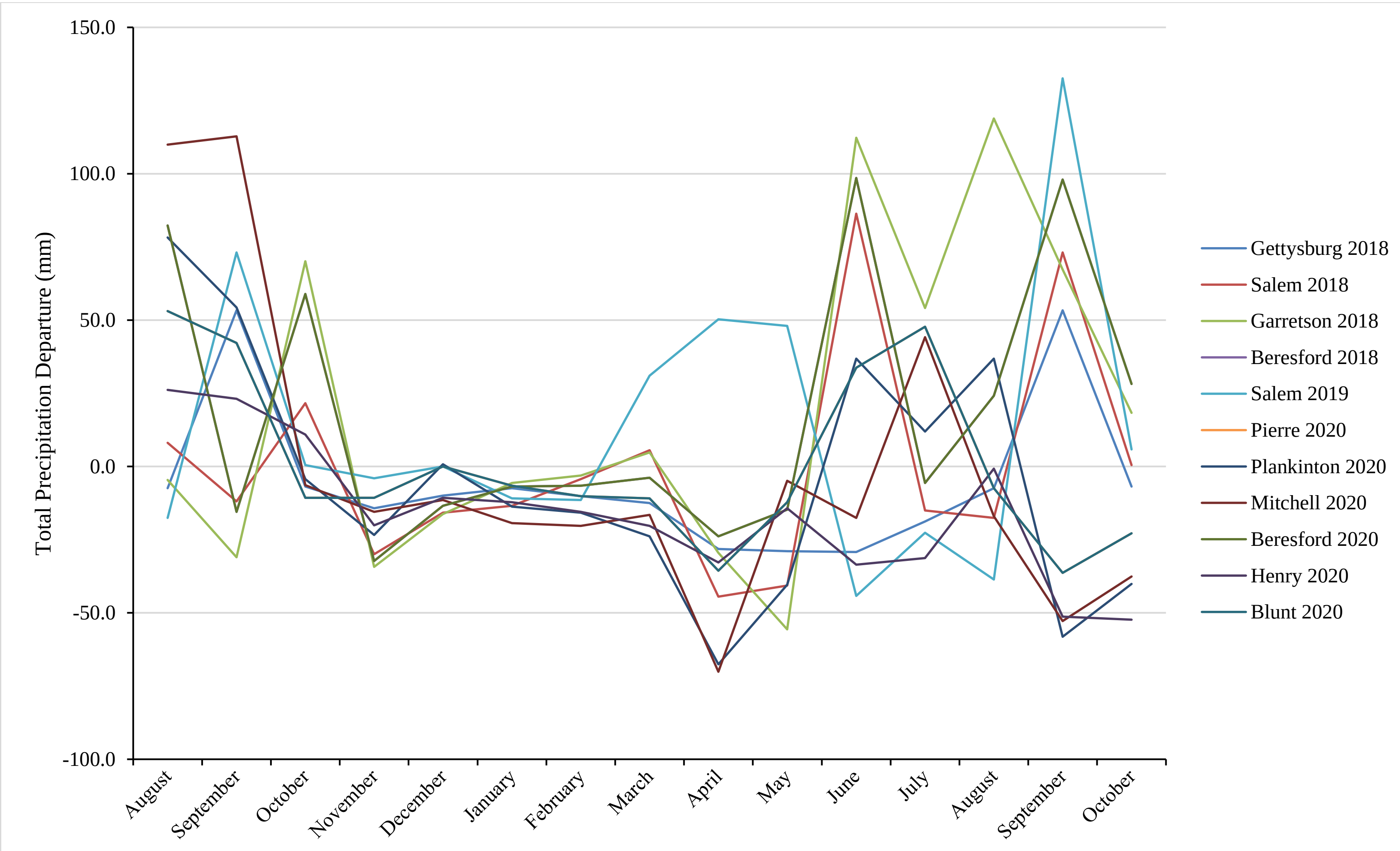

Figure 2-4. Monthly average total precipitation departures (mm) from the 30-year average (1981-2010) at all site-years throughout South Dakota from August when the cover crop was seeded to October of the following year after corn grain harvest.

Table 2-1. Location and dominant soil classification of all site-years.

Site-years	Geographic coordinates	Dominant soil classification
Beresford 2018	43°3'8.88"N 96°53'36.04"W	Fine-silty, mixed, superactive, mesic Udic Haplustolls
Salem 2018	43°44'33.75"N 97° 18'0.09"W	Fine-loamy, mixed, superactive, mesic Typic Haplustolls
Garretson 2018	43°38'47.60"N 96°28'58.75"W	Fine-silty, mixed, superactive, mesic Udic Haplustolls
Gettysburg 2018	44°56'41.97"N 100°1'22.26"W	Fine-silty, mixed, superactive, mesic Typic Argiustolls
Salem 2019	43°43'4293"N 97°18'30.36"W	Fine-loamy, mixed, superactive, mesic Typic Haplustolls
Blunt 2020	44°21'12.15"N 100°0'25.99"W	Fine-loamy, mixed, superactive, mesic Typic Argiustolls
Pierre 2020	44°14'24.56"N 99°59'36.09"W	Coarse-silty over clayey, mixed over smectitic, superactive, mesic Fluventic Haplustolls
Beresford 2020	43°2'24.73"N 96°53'58.29"W	Fine-silty, mixed, superactive, mesic Udic Haplustolls
Mitchell 2020	43°45'1.92"N 98°7'32.94"W	Fine-loamy, mixed, superactive, mesic Typic Haplustolls
Plankinton 2020	43°48'12.82"N 98°30'51.95"W	Fine-loamy, mixed, superactive, mesic Typic Argiustolls
Henry 2020	44°54'43.48"N 97°34'33.39"W	Fine-silty, mixed, superactive, frigid Calcic Hapludolls

Table 2-2. The average NO-3 ppm concentration from 0-15 and 15-60 cm depth in the soil profile, Olsen P ppm, Potassium ppm, percent organic matter, and average pH in the soil.

Site Year	NO-3 (0-15 cm)	NO-3 (15-60 cm)	Olsen P ppm	Potassium ppm	%OM	pH
Garretson 2018	1.9	2.0	7.4	211	4.3	6.4
Gettysburg 2018	4.7	4.7	12.0	625	4.2	6.3
Salem 2018	7.6	6.5	18.5	211	4.5	5.8
Beresford 2018	1.8	1.2	17.7	317	4.7	5.7
Salem 2019	1.7	1.7	39.3	254	4.0	6.8
Blunt 2020	4.2	2.8	8.8	551	4.0	6.8
Pierre 2020	3.5	1.9	15.6	490	3.1	6.6
Henry 2020	5.45	4.6	14.0	146	4.0	6.1
Mitchell 2020	12.8	7.2	13.3	314	4.4	6.9
Plankinton 2020	3.0	2.1	13.3	274	3.6	6.2
Beresford 2020	0.8	0.4	7.6	205	4.2	6.3

Table 2-3. Significance of F tests for the fixed effects of cover crop treatment, site-year, and their interactions on soil health tests including permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), soil respiration, and surface residue from samples collected in the fall and spring across 11 site-years.

	Source of variation		
Variable	**Cover crop (CC)**	**Site-year (S)**	**CC × S**
		***F*-value**	
Surface residue, fall	0.92	51.29*	2.91*
Surface residue, spring	1.36	46.77*	3.94*
POXC, fall	1.30	4.87*	0.99
POXC, spring	1.09	20.71*	0.37
PMN, fall	0.07	23.71*	0.64
PMN, spring	0.20	41.41*	0.71
Soil respiration, fall	0.04	33.04*	1.06
Soil respiration, spring	2.52	70.98*	1.42
		Numerator df	
All variables	3.00	30.00	10.00

*Significant at the 0.05 probability level.

Table 2-4. Effect of cover crop treatments on fall and spring surface residue biomass across 11 site-years.

	Fall					Spring				
Site Year	**Broadleaf**	**Grass**	**Blend**	**Control**	**LSD**	**Broadleaf**	**Grass**	**Blend**	**Control**	**LSD**
	kg ha^{-1}					kg ha^{-1}				
Garretson 2018	4360ab	4420ab	3793b	5281a	1190	2762a	2703a	2123a	2404a	-[b]
Gettysburg 2018	3116a	3161a	2990a	2590a	-	2917a	2913a	3218a	3200a	-
Salem 2018	3837a	4078a	4150a	1667b	741	4270a	4163a	4019a	2661b	798
Beresford 2018	4255a	4478a	4430a	3949a	-	1992a	2022a	1794a	2291a	-
Salem 2019	652a	1316a	682a	778a	-	-	-	-	-	-
Blunt 2020	2330a	2693a	2789a	3545a	-	-	-	-	-	-
Pierre 2020	5419a	5722a	4761a	-	-	1876ab	1863ab	2142a	1591b	396
Henry 2020	-	-	-	-	-	2212a	2712a	2213a	2151a	-
Mitchell 2020	6181a	3694a	4917a	5852a	-	2904a	3036a	2825a	2215a	-
Plankinton 2020	8349a	5569b	7081ab	5548b	1965	3701ab	3474b	5204a	5160a	1481
Beresford 2020	1678a	2045a	2321a	1886a	-	1456a	1691a	1117b	953b	263

Note: LSD is given for each site-year in each sampling period.

[a]Means followed by the same letter in a row within a sampling period are not significantly different (P > 0.05).

[b]Comparisons not available for this site.

Table 2-5. Effect of site-year on soil health measurements permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration, from fall and spring soil samples across 11 site-years.

Site-year	**Fall POXC**	**Spring POXC**	**Fall PMN**	**Spring PMN**	**Fall Soil Respiration**	**Spring Soil Respiration**
	mg/kg of soil		ug/g of soil/week		mg CO_2/g of soil/4days	
Garretson 2018	1059a	946abc	33c	34d	1.68a	2.89a
Gettysburg 2018	869cde	900c	-[b]	-	1.47b	1.57b
Salem 2018	839e	718de	51c	40d	1.31bc	0.79de
Beresford 2018	958bc	1015ab	53c	7d	1.23c	1.13c
Salem 2019	890bcde	874c	168b	176bc	0.88de	0.81de
Blunt 2020	1054a	759d	180b	204ab	0.73ef	1.02c
Pierre 2020	858de	740d	257a	170c	0.45g	0.63e
Henry 2020	930bcde	944bc	151b	199abc	1.18c	0.93cd
Mitchell 2020	936bcd	1018a	260a	223a	0.59fg	1.08c
Plankinton 2020	892bcde	657e	176b	179bc	0.96d	1.08c
Beresford 2020	973ab	932c	231a	168c	0.45g	0.70e

[a]Means followed by the same letter in a column are not significantly different (P > 0.05).
[b]Comparisons not available for this site.

Table 2-6. Pearson correlation coefficients (R values) between fall and spring soil health measurements (permanganate oxidizable carbon (POXC), potentially mineralizable nitrogen (PMN), and soil respiration) and soil properties and weather variables; pH, organic matter (OM), soil test nitrate-N, precipitation, and temperature.

Variable	**OM**	**pH**	**NO_3**	**Precip.**	**Temp.**
Fall POXC	0.18*	0.09	-0.15*	0.18*	0.11
Spring POXC	0.44*	-0.06	-0.18*	0.14	0.16*
Fall PMN	-0.27*	0.38*	0.13	-0.52*	-0.49*
Spring PMN	0.04	0.63*	0.28*	-0.03	-0.46*
Fall soil respiration	0.23*	-0.21*	-0.08	0.25*	0.40
Spring soil respiration	0.15*	-0.12	-0.11	-0.18*	0.24*

*Significant at the 0.05 probability level.

[a]Variables measured in fall or spring were correlated with soil measurements in the same season (ie. Fall PMN ~ Fall OM, Spring PMN ~ Spring OM).

[b]The precipitation totals that were used were from the month of and the month prior of soil sampling.

[c]The temperature average that was used was from the month of soil sampling.

CHAPTER 3: GRASS, BROADLEAF, AND A BLEND OF GRASS AND BROADLEAF COVER CROP EFFECTS ON CORN GRAIN YIELD

3.1 ABSTRACT

Analyzing the effects of single species cover crops on corn grain yield is common practice throughout the U.S Midwest. However, comparing cover crops that include a mixture of many different grass and broadleaf species is limited. This study was conducted throughout central and eastern South Dakota on 11 site-years. Cover crops were planted in the fall after small grains harvest as a dominantly grass mixture, dominantly broadleaf mixture, or a 50/50 grass and broadleaf mixture along with a no cover crop control. Fertilizer-N was applied after spring cover crop termination and before planting corn at six N rates: 0, 45, 90, 135, 200, and 225 kg ha^{-1}. When including a cover crop compared to the control, there were no differences in corn grain yield at economic optimum N rate (EONR), EONR, and economic return 55%, 42%, and 52% of the time, respectively. When there were differences among cover crop mixtures compared to the control, four site-years had a decrease (mean decrease = 1606 kg ha^{-1}) in corn grain yield at EONR, and one site-year had an increase (mean increase = 2657 kg ha^{-1}). Economic profit was reduced when planted under a blend of cover crops at 5 of 11 site-years (mean decrease = US$235 ha^{-1}), grass cover crops at four site-years (mean decrease = US$265 ha^{-1}), and broadleaf cover crops at three site-years (mean decrease = US$296 ha^{-1}). Overall, broadleaf and grass cover crops only increased economic profit at one site-year (mean increase = US$540 ha^{-1}) when compared to the control. In general, growers can plant any cover crop and minimally affect corn grain yield at EONR, EONR, and economic profit.

Abbreviations: N, nitrogen; C, carbon; EONR, economic optimum nitrogen rate

3.1 INTRODUCTION

Cover crops can help alleviate resource management problems by modifying on-farm nitrogen (N) cycles, sequestering N in organic forms for later availability, and reducing negative water quality impacts (Basche et al., 2016; Khan and McVay, 2019). Annual cropping systems remove nutrients from the soil and require annual fertilizer N applications for non-leguminous crops such as corn. Cover crops can be used to inhibit excess N leaching losses from the soil by temporarily immobilizing N within the biomass of cover crops (Gabriel et al., 2012; Tosti et al., 2014). However, the amount of N available to the subsequent corn crop varies depending on the type of cover crop planted (Ranells and Wagger, 1996, 1997; Ruark et al., 2018).

One cover cropping system commonly used is broadleaf cover crops. The lower C:N ratios of broadleaf plants tend to hasten crop residue breakdown because of readily available N to soil microbes compared with the higher C:N ratios of grass cover crops (Ruark and Franzen, 2020b). Since lower C:N ratios of broadleaf cover crops can accelerate residue breakdown, a significant amount of N could become available to the next crop, reducing some of the need for supplemental N applications (Vyn et al., 2000; Magdoff, 2001). However, research in ND concluded that N mineralization timings occurred too soon before the cash crop uptake, leading to excess leaching (Ruark and Franzen, 2020b). These researchers also found no significant increase in corn grain yield following a broadleaf cover crop and therefore suggested that growers should not decrease recommended N (Ruark and Franzen, 2020a). Other research has focused on the effects of some leguminous broadleaf cover crops. Leguminous plants can fix atmospheric N_2 gas into plant-available forms (Ebelhar et al., 1984; Parr et al., 2011; Gentry et al., 2013). At times, legumes can overproduce N, which remains in the soil.

Corn plants can potentially use this leftover N for grain production, potentially lowering N fertilizer requirements (Herridge et al., 1990; Clark et al., 1994; Ranells and Wagger, 1996; Odhiambo and Bomke, 2001; Parr et al., 2011; Alvarez et al., 2017). Research has shown that no-till corn grain yield has increased when following broadleaf leguminous cover crops (Ebelhar et al., 1984; Parr et al., 2011; Gentry et al., 2013). Research conducted by Yang et al. (2019) concluded that legume cover crops could eliminate the need for chemical fertilizers while maintaining corn grain yields equivalent to conventionally produced corn. However, N fertilizer is still applied because legume cover crops have not consistently shown a definite amount of N fixation for the following corn crop (Gentry et al., 2013; Redfern, 2016).

Grass cover crop mixtures have a fibrous root system, which allows them to scavenge for and immobilize soil nitrate-N, preventing nitrates from leaching into groundwater. Other benefits of grass cover crops include a ground cover that increases water infiltration rates and slows down evaporation during the growing season (Sullivan et al., 1991; Kaspar et al., 2007, 2012; Currie et al., 2008). Soil moisture conservation during the spring and early summer months could benefit corn growth during the drier summer months. (Sullivan et al., 1991; Subedi-chalise, 2017). Research in central IA showed that a winter-hardy cereal rye cover crop improved water holding capacity during both wet and dry years, resulting in enhanced corn yield during dry years (Basche et al., 2016). Grass cover crops increased soil aggregate size by 55% after four years of planting, contributing to the overall water holding capacity (Rorick and Kladivko, 2017). Grass and broadleaf cover crops can have a differing effect on soil aggregation. During a 12-year study, grass cover crops improved soil aggregate stability, but broadleaves did not have the same effect (Black, 1994). Soil aggregation improvements could explain why farmers have found minor corn and soybean yield increases with the implementation of cereal rye cover crops (Black, 1994; Roesch-Mcnally et al., 2018). Although grass cover crops have been shown to increase soil water holding capacity and aggregate stability, they may also change N requirements. Grass cover crops tend to have higher C:N ratios, leading to a slower decomposition of crop residues (Gentry et al., 2013). These higher C:N ratios in plant residue can increase short-term N immobilization (Ranells and Wagger, 1996; Odhiambo and Bomke, 2001; Gentile et al., 2008; Gentry et al., 2013). Slower N mineralization can make it more difficult for corn to take up N because less is plant available and is especially a problem when corn N demand is highest, creating a need for increased fertilizer (Ranells and Wagger, 1997; Odhiambo and Bomke, 2001). Other studies have shown that corn N requirements do not change when planting grass cover crops (Vyn et al., 2000; Ruark and Franzen, 2020a). These studies show the importance of soil nitrate tests after starting cover cropping practices because cover crops change the speed that N cycles in the soil.

Grass or broadleaf dominant cover crops may be too extreme for soil nutrient cycling. Under broadleaf dominant cover crops, the soil may have a high mineralization rate due to the low C:N ratios of broadleaf plants (Ranells and Wagger, 1997; Odhiambo and Bomke, 2001; Gentry et al., 2013; Yang et al., 2019). In contrast, N immobilization can occur with grass dominant cover crops for more extended periods than broadleaf cover crops because of higher C:N ratios. Both grass and broadleaf dominant cover crop blends have benefits and drawbacks for addressing natural resource management and soil conservation. A combination of broadleaf and grass cover crops having low and high C:N ratios may add balance to the cropping system.

Grass cover crops mixed in with legumes can scavenge any additional N produced by legumes and other mineralized soil organic N sources (Clark et al., 1994; Ranells and Wagger, 1996, 1997; Odhiambo and Bomke, 2001; Tosti et al., 2014). Studies focusing on pure stands of barley and hairy vetch showed that grass and legume species coexisted well together because the barley scavenged the leachable N produced by the hairy vetch (Tosti et al., 2014). The added biodiversity of legumes and grasses has been shown to improve microbial structure and function, soil function and stability, and possibly corn yield (Strickland et al., 2019). Cover crop blends create a favorable situation where the benefits outweigh drawbacks while making a cocktail of biodiversity in the soil.

Planting a grass and broadleaf blend of cover crops is an excellent combination to gain the yield-protecting benefits from both types of cover crops. Previous studies have shown that every kind of cover crop mixture has its advantages and drawbacks in corn grain production. Cover crops can add or remove plant-available soil N at different times while conserving other nutrients and water resources. Grass and broadleaf blends have been shown to balance each other out with broadleaf cover crops producing more plant-available N with low C:N ratios and leguminous effects, while grass cover crops sequester that plant-available N for future corn crops (Ranells and Wagger, 1997; Gentry et al., 2013; Yang et al., 2019). However, a limited number of studies compared the effect of multi-species blends of cover crops to single grass and broadleaf cover crops on corn grain yield and the N rate required to obtain that yield. Therefore, this study's objective was to determine the impact of broadleaf and grass (single and mixed species) cover crops compared to a no cover crop control on economic optimum nitrogen rate (EONR), corn grain yield at EONR, and economic return.

3.2 MATERIALS AND METHODS

3.2.1 Experimental Design

This study was conducted in eastern and central South Dakota from the fall of 2017 to the fall of 2020 on 11 site-years. The research sites are listed by geographic location, coordinate points, and soil classification in Table 2-1. The experiment was conducted as a split-plot design, replicated four times. The whole plot treatments were four cover crop treatments, and the sup-plot treatments were six corn N rates.

Each whole plot size was 27 m in length and 7.5 m in width. The four whole plot cover crop treatments were: 1) dominantly grass mixture, 2) dominantly broadleaf mixture, 3) a 50/50 blend of grass and broadleaf species, and 4) a control (no cover crop). The dominantly grass mixture included 22.5% oats (*Avena sativa*), 22.5% barley (*Hordeum vulgare*), 22.5% foxtail millet (*Setaria italica*), 22.5% sorghum/sudangrass (*Sorghum x drummondii*), 2.5% radish (*Raphanus sativus*), 2.5% turnip (B*rassica rapa subsp. Rapa*), 2.5% pea (*Pisum sativum*), and 2.5% lentil (*Lens culinaris*). The dominantly broadleaf mixture included 2.5% oats, 2.5% barley, 2.5% foxtail millet, 2.5% sorghum-sudan grass, 22.5% radish, 22.5% turnip, 22.5% pea, and 22.5% lentil. The 50/50 grass/broadleaf mixture included 12.5% of all the previously discussed cover crop species. Cover crops were planted after harvest of winter wheat or oats (Salem and Beresford were oats) (Table 3-1).

Each N rate subplot size was 7.5 m in length and 4.5 m in width. The subplot fertilizer-N rates were 0, 45, 90, 135, 200, and 225 kg ha^{-1}. Urea (46% N) with 0.85%

dicyandiamide and 0.06% N-(n-butyl) thiophosphoric triamide (NBPT) (Super-U [Koch Agronomic Services, Wichita, KS]) was hand broadcast throughout each plot with a single application one week before planting on the soil surface.

Farmer-cooperators chose the corn hybrid and planted corn on research areas at populations and row spacings (40, 50, 57, or 75 cm apart) the same as the rest of the field (Table 3-1). Corn grain was harvested mechanically with a small plot combine in the fall from the center two rows of each 75 cm row spacing plot and the center three rows from each 40, 50, and 57 cm row spacing plot. Grain moisture was used to adjust grain yield to 15.5% moisture.

3.2.2 Sampling and Analysis

Twelve soil samples were collected from each replication of each cover crop treatment in the spring one week before planting from a depth of 0 to 15 cm and 15 to 30 cm using a soil probe with an inside diameter of 1.9 cm. Soil samples were air-dried and ground to pass through a 2 mm sieve. These soil samples were analyzed for general soil fertility measurements (NO_3-N 0-15 cm and 15-60 cm, Olsen P ppm, potassium ppm, % OM, and pH tests) following the recommended chemical soil test procedures for the North Central Region (NCR221, 2015) (Table 2-2). Only soil NO_3–N was analyzed at the 0 to 15 and 15 to 30 cm depths. All others were only analyzed using the 0 to 15 cm depth.

3.2.3 Statistical Analysis

Statistics were completed with SAS software version 9.4 (SAS Institute Inc., Cary, NC). A split-plot design was used as the experimental design with four replications with cover crop treatment as the main plot and N rate as the subplot with six N rates. Since the interaction of cover crop and N rate with site-year was significant, each site-year was analyzed separately. The REG and NLIN procedures were used to calculate EONR using the methods described in Clark et al. (2019). Briefly, linear, linear plateau, quadradic, and quadradic plateau models were used to determine the effect of N rate on corn grain yield for each cover crop treatment (Cerrato and Blackmer, 1990; Sawyer et al., 2006; Scharf et al., 2005). Models were compared using the metrics of model probability significance and coefficient of determination. The best fit model among the four was selected. The EONR was calculated by using an N price of US$0.88 kg^{-1} and a corn grain price of US$0.16 kg^{-1} for each cover crop treatment. If a cover crop treatment at a particular site-year was identified as non-responsive to N application because there was no plateau reached, the EONR was set as 0 kg N ha^{-1}. If a linear model was the best model to describe corn grain yield response to N, the EONR was set as the highest soil test nitrate-N plus fertilizer-N rate for that site-year. To determine differences in EONR of the four cover crop treatments, the N rates where the profit was ±US$2.47 of EONR were determined, excluding the sites where there was no response to N and where the response was linear following Clark et al. (2019). Then the difference between the upper and lower N limits was averaged across site-years and cover crop treatments. Using this methodology, a significant difference between the EONR of cover crop treatments was determined to be ±16 kg N ha^{-1}.

Grain yield at EONR was calculated by using the EONR and the chosen model. To determine differences in grain yield at EONR among the four cover crop treatments, the amount of N needed per kg of grain produced was calculated and averaged across cover crop treatments and site-years (0.02 kg N kg^{-1} corn) and then multiplied by the ±16 kg N ha^{-1} value used to determine the significant difference between EONR values. This methodology resulted in significant differences in grain yield at EONR among cover crop treatment to be ± 1000 kg ha^{-1}. Economic return was calculated by taking the profit from corn grain yield at EONR using a corn grain price of US$0.16 kg^{-1} and subtracted the cost of the fertilizer-N cost at US$0.88 kg^{-1}. To determine differences in economic return among the four cover crop treatments, we determined the profit from the 1000 kg ha^{-1} significant difference in corn yield and subtracted the fertilizer cost from the 16 kg N ha^{-1} significant difference in EONR. This methodology resulted in significant differences in economic return among cover crop treatment to be ± US$145 ha^{-1}.

3.3 RESULTS AND DISCUSSION

3.3.2 Weather

Temperatures and precipitation during the cover crop growing season were adequate for establishment. Corn was planted in May, one week after remaining cover crops were chemically terminated with 3227 mL ha^{-1} of glyphosate. Weather was recorded using South Dakota Mesonet. The average monthly temperatures of this period ranged from 11.7 to 23.9 °C (Figure 2-1). The monthly average temperature departure from normal varied among site-years, but most site-years were within 3°C of normal. The only exception was the month of May when temperatures at Garretson 2018 and Gettysburg 2018 rose above average by 4°C (Figure 2-2). Monthly precipitation during the corn growing season ranged from 6.1 to 211.8 mm (Figure 2-3). Generally, precipitation was within 50 mm of average except for Garretson 2018, when June through September was above average (>50 mm of average) (Figure 2-4**)**. Salem 2018 and Beresford 2020 were also above-average precipitation in June and September and Salem 2019 in September. However, the precipitation levels for Henry 2020, Mitchell 2020, Pierre 2020, and Blunt 2020 were about 50 mm below average during September and October. The highest monthly precipitation occurred in September at Salem 2019 (+132.6 mm mean deviation) **(**Figure 2-1**)**. Overall, precipitation was adequate to sustain corn growth.

3.3.3 Corn Grain Yield at Economic Optimum Nitrogen Rate

Corn grain yield at EONR was influenced by the interaction of N rate, cover crop, and site-year (Table 3-2). The overall range in yield at EONR ranged from 6340 to 14688 kg ha^{-1}, the average yield being 10415 kg ha^{-1} (Table 3-3). The broadleaf, grass, blend, and no cover crop control treatments had average yields at EONR of 10260, 10573, 10145, and 10682 kg ha^{-1}, respectively. When averaged across 11 site-years, these results show that all cover crop mixtures were similar to the no cover crop control.

When compared among site-years, different cover crop mixtures varied in which site-years had a similar, higher, or lower corn grain yield at EONR than the control (Table 3-3). Overall, each cover crop mixture (broadleaf, grass, or blend) compared to the control had a similar corn grain yield at EONR in 6 of 11 (55%) site-years, a reduced grain yield in 4 (36%) site-years (-1130 to -2574 kg ha^{-1}; mean = -1606 kg ha^{-1}), and a greater grain yield in 1 (9%) site-year (+1129 to 48333 kg ha^{-1}; mean = +2657 kg ha^{-1}). These results indicate that corn yield is highly variable among different cover crop treatments compared to the control, but generally, there was a minimal change in corn grain yield compared to the no cover crop control. A study in WI and ND showed that broadleaf cover crops also did not increase or decrease corn grain yield at EONR (Ruark and Franzen, 2020a). However, another study showed that corn grain yield at EONR was decreased after planting a grass (cereal rye) cover crop compared to a no cover crop control (Pantoja et al., 2015). These results agree with most of our results (10 of 11 site-years), which found that grass does not increase or decrease corn grain yield at EONR compared to the control.

The minimum corn grain yield at EONR among the three cover crop mixtures (broadleaf, grass, and blend) was 6904 kg ha^{-1}, the maximum yield was 13746 kg ha^{-1}, and the average yield was 10326 kg ha^{-1} (Table 3-3**)**. Among cover crop mixtures, 8 of 11 (73%) site-years had similar corn grain yield at EONR between broadleaf and grass (Table 3-3). Broadleaf cover crops had a lower corn grain yield than grass cover crops at 2 (18%) site-years (-1695 to -2825 kg ha^{-1}; mean = -2260 kg ha^{-1}) while having greater yield at 1 (9%) site-year (+1004 kg ha^{-1}). When comparing grass and blend cover crops, 9 of 11 (82%) site-years were similar in corn grain yield, while grass had increased corn grain yield at 2 (18%) site-years (+1067 to 4269 kg ha^{-1}; mean = 2668 kg ha^{-1}). When comparing blend to broadleaf cover crops, 8 of 11 (73%) site-years had similar corn grain yield. However, in 2 (18%) site-years, broadleaf had higher corn grain yield than blend (+1256 to 1444 kg ha^{-1}; mean = 1350 kg ha^{-1}) while in 1 (9%) site-year, the blend had a higher yield (+2259 kg ha^{-1}). These results indicate that generally, similar corn grain yield at EONR can be expected among the three cover crop mixtures. However, when differences did occur, grass tended to have a higher corn yield than broadleaf and blend, and broadleaf to have a higher yield than blend, but these results were not consistent enough to explain why this occurred. A study that found differing results from ours looked at winter cover crops’ effect on cotton and sorghum yield. They found that a broadleaf (hairy vetch) and grass (cereal rye) biculture blend increased yield in both cotton and sorghum crops compared to an only hairy vetch or only cereal rye cover crop

(Sainju, 2009). Another study that differed from ours found that when comparing a grass cover crop (oats) and a broadleaf cover crop (radish), oats reduced corn grain yield by 4% when compared to the radish cover crops (Rutan and Steinke, 2019). The similar effect on corn grain yield at EONR among our three cover crop mixtures compared to other studies may be due to the greater diversity of grass and broadleaf species in each cover crop mixture in our study relative to these other studies that mainly focused on one grass or broadleaf species in a mix. Differences compared to other studies may also be due to our study being a first-year comparison of cover crops in a field, and other studies were based on longer-term trials (greater than three years).

3.3.4 Economic Optimum Nitrogen Rate

The EONR ranged from 0 to 285 kg $ha^{-1,}$ with the average being 138 kg ha^{-1} (Table 3-3). The broadleaf, grass, blend, and no cover crop control treatments had average EONRs of 135, 133, 155, and 131 kg ha^{-1}, respectively. When averaged across 11 site-years, these results show that broadleaf, grass, and control averaged a similar EONR to each other, and the blend cover crop averaged a greater EONR than all other treatments.

When compared among site-years, different cover crop mixtures varied in which site-years had a similar, higher, or lower EONR than the control (Table 3-3). Overall, both broadleaf and grass cover crop mixtures compared to the control had a similar EONR at 5 of 11 (46%) site-years, a reduced EONR at 3 (27%) site-years (-23 to -179 kg ha^{-1}; mean = -68 kg ha^{-1}), and a greater EONR at 3 (27%) site-years (+42 to 229 kg ha^{-1}; mean = +84 kg ha^{-1}). The blend cover crop mixture compared to the control had a greater EONR at 6 (55%) site-years (19 to 93 kg ha^{-1}; mean = 57 kg ha^{-1}), a similar EONR at 4

(36%) site-years, and a reduced EONR at 1 (9%) site-year (-59 kg ha^{-1}). These results indicate that dominantly grass or broadleaf cover crops normally have a minimal effect on EONR, but when there are differences, they are equally likely to increase or decrease the EONR. However, the blend mixture compared to the control generally needed extra N fertilizer to optimize grain yield (55% of the time) and, to a lesser extent, did not affect EONR (36% of the time). A study in WI found similar results to ours; a broadleaf mixture did not change EONR consistently and recommended to keep applying the same amount of N fertilizer as if no cover crops were being grown (Ruark and Franzen, 2020b). However, other studies found that a blend of grass and broadleaf cover crops deliver an intermediate supply of N through better combinations of C:N ratios to the corn crop, meaning that there is a possibility of decreased EONR (Tosti et al., 2014).

The minimum EONR among the three cover crop mixtures (broadleaf, grass, and blend) was 0 kg ha^{-1}, the maximum EONR was 343 kg ha^{-1}, and the average EONR was 141 kg ha^{-1} (Table 3-3). Among cover crop mixtures, broadleaf cover crops had a lower EONR than grass cover crops at 6 of 11 (55%) site-years (-28 to -25 kg ha^{-1}; mean = -54 kg ha^{-1}), a similar EONR at 2 (18%) site-years, and a higher EONR at 3 (27%) site-years (+33 to 90 kg ha^{-1}; mean = +117 kg ha^{-1}). When comparing grass and blend cover crop mixtures with each other, the grass had a greater EONR than the blend at 4 of 11 (36%) site-years (+15 to 46 kg ha^{-1}; mean = 31 kg ha^{-1}), a lessor EONR than the blend at 4 (36%) site-years (-167 to -41 kg ha^{-1}; mean = -91 kg ha^{-1}), and a similar EONR at 3 (27%) site-years. When comparing blend to broadleaf cover crops, 7 of 11 (64%) site-years had a similar EONR with each other, broadleaf had a lower EONR than the blend at 3 (27%) site-years (-272 to -19 kg ha^{-1}; mean = -139 kg ha^{-1}) and had a greater EONR than blend at 1 (9%) site-year (229 kg ha^{-1}). These results indicate that broadleaf compared to grass cover crops generally reduced the EONR of corn. The likelihood of EONR being different (greater or reduced) or similar between grass and blend cover crops was similar. However, broadleaf compared to the blend of cover crops were more likely to result in a similar EONR. Some studies showed that a blend of broadleaf and grass cover crops could be an intermediate cover crop mixture involving plants with a high and low C:N ratio to deliver N at appropriate times to the corn, which can result in reducing the EONR (Ranells and Wagger, 1997; Tosti et al., 2014). We found similar results as these studies with the blend being an intermediate option to an only grass or broadleaf mixture with the majority of the blend being similar or decreasing EONR to maximize yield compared to the single species mixtures. The similarities of the blend cover crop being an intermediate EONR between cover crop mixtures is most likely due to the many different plant species in the blend, meaning there is a greater possibility for that happy medium EONR to be the ending result.

3.3.5 Economic Return

Our results varied whether a similar, lower, or greater EONR resulted in a similar trend in corn grain yield, making it difficult to determine the best option among the cover crop treatments. Therefore, we used a simple economic return analysis to combine the corn grain yield at EONR and EONR results into one variable. To do this, we multiplied corn grain yield at EONR by the price of corn and subtracted the cost of nitrogen fertilizer at the EONR for each cover crop treatment. (See methods for more details). The overall range in economic return was US$820 to US$2311 ha^{-1}, the average economic return being US$1517 ha^{-1} (Table 3-4). The broadleaf, grass, blend, and no cover crop control treatments had average economic returns of US$1495, US$1547, US$1460, and US$1566 ha^{-1}. When averaged across 11 site-years, these results show that the three cover crop mixtures had a similar economic return compared to the no cover crop control.

When compared among site-years, different cover crop mixtures varied in which site-years had a similar, higher, or lower economic return than the control (Table 3-4). When comparing the broadleaf cover crop to the control, there was a similar economic return in 7 of 11 (66%) site-years, a reduced economic return at 3 (27%) site-years (-US$165 to -US$517 ha^{-1}; mean = -US$296), and greater economic return at 1 (9%) site-year (+US$277 ha^{-1}). When comparing a grass cover crop to the control, there was a similar economic return in 6 of 11 (55%) site-years, a reduced economic return in 4 (36%) site-years (-US$191 to -US$375 ha^{-1}; mean = -US$264 ha^{-1}), and an increased economic return in 1 (9%) site-year (+US$802 ha^{-1}). When comparing the blend cover crop to the control, there was a similar economic return in 6 of 11 (55%) site-years, a reduced economic return in 5 of 11 (46%) site-years (-US$146 to -US$405 ha^{-1}; mean = -US$235 ha^{-1}), and none of the site-years had an increase in economic return when planted under a blend cover crop. These results indicate that in the first year of planting broadleaf, grass, or a blend of cover crops, the economic return is normally similar or reduced compared to when no cover crops were planted. However, long-term trials are needed to understand better the influence of cover crops on economic return over time, as research has shown changes in soils after the start of including cover crops can take approximately three to seven years before consistently showing changes in soil physical, chemical, and biological properties (Ranells and Wagger, 1997; Wiedenhoeft and Cambardella, 2013; Gonzalez-Maldonado, 2019)

The minimum economic return among the three cover crop mixtures (broadleaf, grass, and blend) was 4862 ha^{-1}, the maximum economic return was US$2163 ha^{-1}, and the average economic return was US$1501 ha^{-1}. Among cover crop mixtures, broadleaf cover crops had a similar economic return as a grass cover crop at 8 of 11 (73%) site-years, a reduced economic return than grass at 2 (18%) site-years (-US$525 to -US$207 ha^{-1}; mean = -US$366), and greater economic return at 1 (9%) site-year (+US$152). Grass cover crops had a similar economic return as the blend at 9 (82%) site-years, and a greater economic return at 2 (18%) site-years (+US$155 to US$760; mean = +US$458). Broadleaf had a similar economic return as the blend at 7 (64%) site-years, increased economic return at 3 (27%) site-years (+US$181 to US$235; mean = US$205), and decreased economic return at 1 (9%) site-year (-US$244). These results indicate that all three cover crop mixtures normally had a similar economic return value. Of the three cover crop mixtures evaluated, planting a blend of grass and broadleaf cover crops most often resulted in the greatest economic return while only reducing the economic return once.

3.3.4 Conclusion

Including a broadleaf, grass, or grass/broadleaf blend of cover crops after small grain harvest and terminating before corn planting had a varying effect on corn grain yield at EONR, EONR, and economic profit. Generally, the broadleaf, grass, and the blend cover crops had similar corn grain yield compared to the control while having mostly decreased corn grain yield at other site-years. Broadleaf, grass, and a blend generally had similar economic returns when compared to the control. However, the blend had a greater number of site-years that had a decrease in economic return than the broadleaf only and the grass only cover crops. In contrast, the grass and broadleaf cover crops only ever increased the economic return once compared to the control, and the blend never increased the economic return. Although the control showed a similar EONR, varying effects were discovered among different cover crop mixtures at various site-years 58% of the time, indicating a higher and lower difference between cover crop treatments and the control. Among cover crops, the broadleaf, grass, and blend mixtures generally had the same corn grain yield at EONR. Although corn grain yield was higher after a grass cover crop at one more site-year than broadleaf, broadleaf and grass were similar when comparing the number of site-years with higher or lower corn yield at EONR and EONR itself to the control. For decreasing the amount of N needed for optimal corn grain yield, the blend of grass and broadleaf cover crops would be the best option. However, with this option, there was a greater probability that corn grain yield and economic return would shrink compared to the grass, broadleaf, or control even though less N was being added to get to optimal corn grain yield. Long-term studies are needed to determine if and how these findings change over time.

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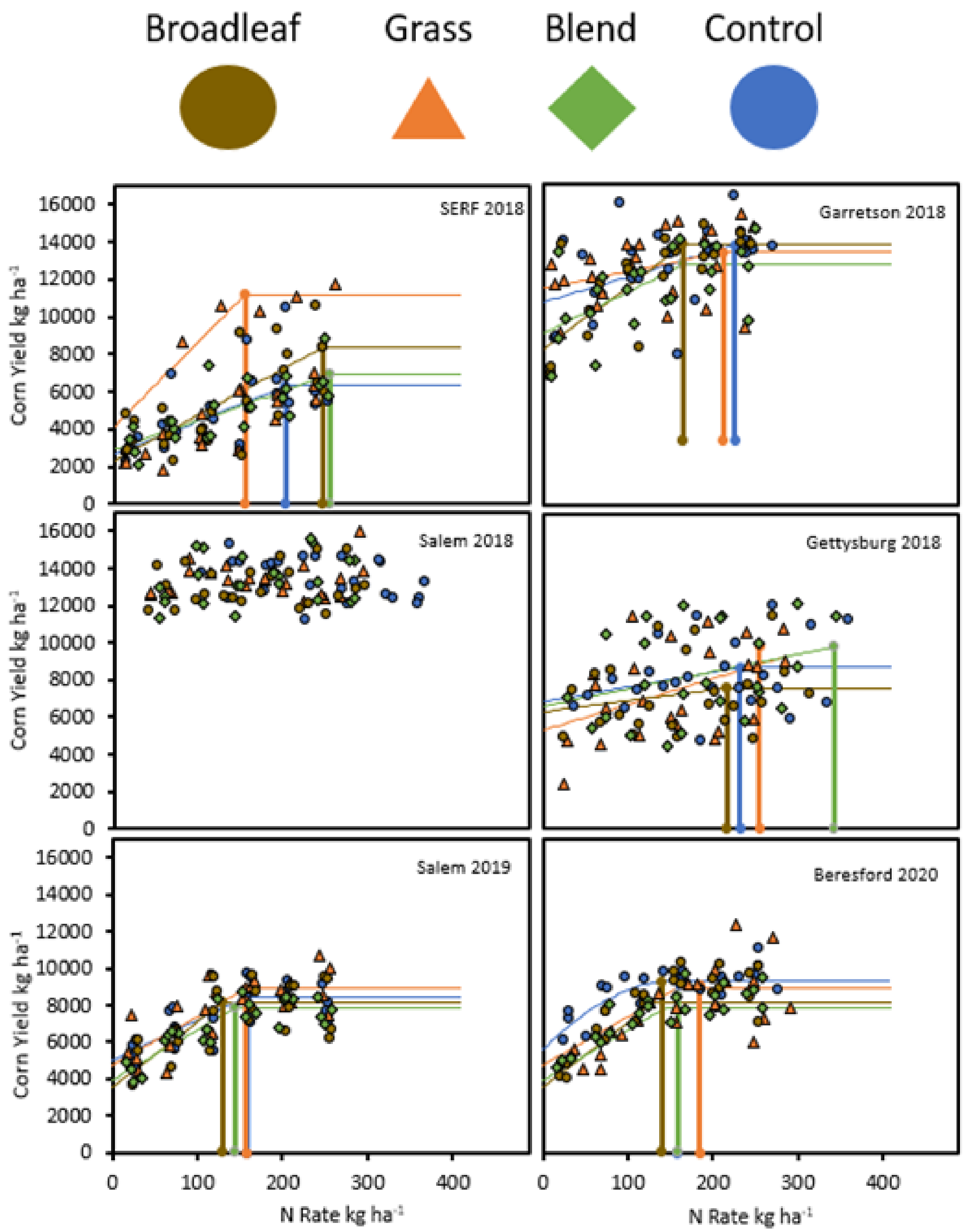

Figure 3-1. Relationship between N rate (kg ha^{-1}) and corn grain yield (kg ha^{-1}) compared among four cover crop treatments: broadleaf, grass, blend, and control across six site-years throughout South Dakota.

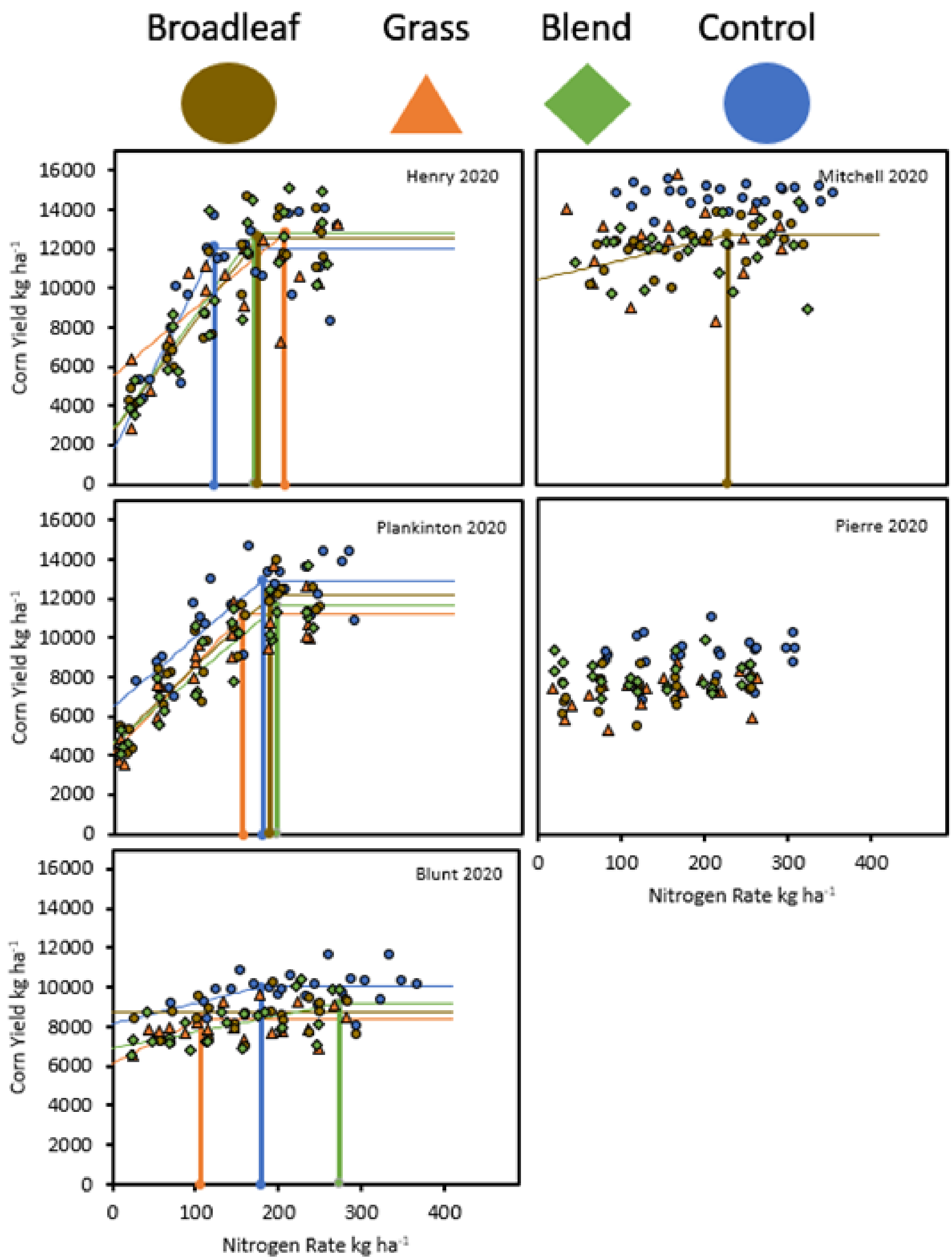

Figure 3-2. Relationship between N rate (kg ha^{-1}) and corn grain yield (kg ha^{-1}) compared among four cover crop treatments: broadleaf, grass, blend, and control across five site-years throughout South Dakota.

Table 3-1. Previous crop, years of no-till, row spacing, corn hybrid, and corn population of all site-year.

Site-year	Previous crop	No-till years	Row Spacing (cm)	Hybrid	Population (seeds ha^{-1})
Beresford 2018	oats	6	76	Pioneer P0046AM	76,601
Salem 2018	oats	25	51	Pioneer P9772AM	75,366
Garretson 2018	winter wheat	26	76	Dekalb DKC49-72	77,837
Gettysburg 2018	winter wheat	29	76	Dekalb DKC47-54	67,953
Salem 2019	oats	26	51	Pioneer P0075Q GC	75,366
Beresford 2020	oats	7	76	Pioneer P0339AM	76,601
Mitchell 2020	winter wheat	28	57	Dekalb DKC50-84RIB	76,601
Plankinton 2020	winter wheat	16	51	Channel 203-01VT	69,188
Pierre 2020	winter wheat	30	51	Pioneer P9998AM	55,597
Blunt 2020	winter wheat	20	76	Dekalb DKC47-47RIB	51,891
Henry 2020	winter wheat	1	76	Mycogen 92D51	73,512

Table 3-2. Significance of F tests for the fixed effects of cover crop, N rate, site-year, and their interactions on corn grain yield across 11 site-years.

Source of variation	***F*-value**
Cover Crop (CC)	28.99*
N Rate (N)	439.08*
Site-year (S)	219.29*
CC × N	4.49*
CC × S	3.12*
N × S	30.27*
CC × N × S	0.71*

Table 3-3. Effects of cover crops on the economic optimum N rate (EONR) and the corn grain yield at the EONR across 11 site-years.

	Yield at EONR				EONR			
Site-year	**Broadleaf**	**Grass**	**Blend**	**Control**	**Broadleaf**	**Grass**	**Blend**	**Control**
	kg ha^{-1}							
Beresford 2018	8348b	11173a	6904c	6340c	245a	155c	254a	202b
Salem 2018	13181a	13683a	13746a	13495a	0a	0a	0a	0a
Garretson 2018	12240a	11800ab	10984b	12240a	166b	212a	166b	225a
Gettysburg 2018	7595c	9290ab	9854a	8725b	216c	285b	343a	231c
Salem 2019	8160ab	8913a	7846b	8474ab	130b	158a	143ab	158a
Beresford 2020	9290a	9101a	8536a	9352a	140c	185a	159b	143c
Mitchell 2020	12679b	12302b	12114b	14688a	229a	0b	0b	0b
Plankinton 2020	12177ab	11173c	11675bc	12930a	188ab	155c	196a	178ab
Pierre 2020	7846b	7658b	7971b	9164a	0a	0a	0a	0a
Blunt 2020	8787b	8411b	9164ab	10043a	0d	105c	272a	179b
Henry 2020	12553a	12805a	12805a	12051a	172b	204a	169b	120c

Note. Significant differences were determined for EONR at ±16 kg ha^{-1} and yield at EONR at ±1000 kg ha^{-1}.

Table 3-4. Effects of cover crops on economic return to N (N) at the economic optimum N rate (EONR) across 11 site-years.

	Economic return[a]			
Site-year	**Broadleaf**	**Grass**	**Blend**	**Control**
	US$ ha^{-1}			
Beresford 2018	1097b	1622a	862c	820c
Salem 2018	2074a	2153a	2163a	2124a
Garretson 2018	1780a	1670ab	1582b	1728a
Gettysburg 2018	1004b	1211a	1248a	1169a
Salem 2019	1169ab	1263a	1108b	1194ab
Beresford 2020	1338a	1269a	1203a	1345a
Mitchell 2020	1794b	1936b	1906b	2311a
Plankinton 2020	1750ab	1622ab	1664b	1878a
Pierre 2020	1235b	1205b	1254b	1442a
Blunt 2020	1383a	1231b	1202b	1422a
Henry 2020	1824a	1835a	1866a	1791a

Note. Significant differences were determined for economic return at ±USUS$145 ha^{-1}.
[a]Economic return = Revenue (price of corn grain * yield) – cost of N fertilizer.

4.1 Advantages and Limitations

This research project had several advantages. The main advantage of this project was that we were able to compare the influence of cover crops using a dominantly broadleaf, dominantly grass, and a blend of both broadleaf and grass mixtures against soil health measurements, yield at economic optimum nitrogen (N) rate (EONR), EONR, and economic return. To add on to the effect of these comparisons of yield and N rate using different cover crop mixtures, we utilized six N rates in each cover crop mixture, including the no cover crop control to get an accurate N rate that was used to calculate both the optimal corn grain yield and the optimal N rate. Other experiments normally only utilized one or two N rates against the cover crop treatments they were comparing to make a general estimate about how cover crops affected fertilizer-N requirements.

Nitrogen rates on cover crops can be affected by different soil types, local environments, and different locations. This trial was replicated over the course of 11 site-years that sprawled throughout eastern and central South Dakota. To achieve this goal, both private on-farm plots and university research stations were used. This was also an advantage because it showed that these experiments could be easily incorporated into a working farm system and not just a research station type of implementation. These implementations offer the simple practicality of the use of cover crops, and that these results can be seen on farmer-owned farms and research farms.

Some limitations were a part of this research project that may have inhibited the overall test of how cover crops can affect the South Dakota cropping system. The first of these was that the different cover crops were not to be compared for more than the first year of implementation. A broadleaf, grass, and blend of these broadleaf and grass species were only planted and compared for one year, and a different location was evaluated the following year. Although this did give the benefit of being able to compare first year comparison effects, cover crops may take extended amounts of time to make a measurable difference in the soil, to corn grain yield, and EONR.

The second limitation was the way surface residue collection was handled. The samples collected were full amounts of surface residue and biomass of the growing cover crops. This is a great way to understand a partial effect on how different cover cropping systems can affect carbon and N cycles. However, if we are to understand how previous crop residues cycle back into the soil, living biomass needs to be partitioned from dead biomass, so we know what is new and old. From there, we can separate grasses and broadleaf plants in both the cover crop mixtures and previous corps. This would altogether help us gain knowledge of how much organic matter is being added to the overall cropping system.

The third limitation was the planting of broadleaf cover crops within the grass mixture and planting grass cover crops within the broadleaf mixture. Ten percent of the broadleaf mixture was grasses and vice versa. Although this brings added diversity to the cropping system, it is inherently a good cover cropping practice and is practical in the farming world; it makes it difficult to compare all grasses and all broadleaf mixtures to a blend of these cover crops. Future studies could use a mixture of 100% broadleaf and 100% grass while adding in a mix of both broadleaf and grasses to allow for a better comparison. To make this more beneficial to the research that was completed, there should be a mixture of 100% broadleaf and 100% grass for a complete and accurate comparison among types of cover crop species.

4.2 Conclusions

This study was conducted to determine the effect of different grass and broadleaf cover crop mixtures (single and mixed species) compared to the no cover crop control and among other cover crop mixtures on common biological soil health measures. Additionally, the impact of single and mixed cover crop species compared to the no cover crop control and among the three cover crop mixtures on corn grain yield at EONR, EONR, as well as economic profit.

This three-year, first-year comparison of three mixtures of cover crops: grass, broadleaf, and a grass and broadleaf blend, showed there to be minimal effects on surface residue and the three common biological soil health measurements used compared to the no cover crop control and among each other. Since surface residue was not changed on 7 of 11 site-years compared to the control regardless of cover crop composition, there is reason to believe that the inclusion of cover crops accelerated the rate of decomposition of previous crop surface residue. This increased decomposition may have enhanced the rate of adding organic matter to the soil.

When comparing the three cover crop mixtures to the no cover crop control, there were varying effects on corn grain yield at EONR, EONR, and economic profit. The cover crop mixtures mostly had similar corn grain yield compared to the control, but at times decreased yield while rarely increasing the yield. Comparing among the three cover crop mixtures, corn grain yield was similar most of the time while grass and broadleaf produced better yield than the blend slightly more of the time. The EONR was affected by cover crops about half of the time compared to the control, while the grass and broadleaf increased and decreased EONR at equal amounts of site-years. The blend mostly increased the EONR compared to the control, only decreasing it one time. The EONR among cover crops showed that broadleaf cover crops generally reduced EONR compared to the grass. The grass cover crop also increased and decreased the EONR an equal number of times compared to the blend, while the broadleaf and blend generally affected EONR similarly. The economic profit was generally not influenced by any cover crop mixture compared to the control. However, the blend and grass cover crops tended to reduce the economic profit compared to the control more frequently than the broadleaf did, meaning a greater chance for economic return by planting a broadleaf cover crop. Among cover crops, the economic return was generally equal with few variations of increasing and decreasing of economic profits at various site-years. To better determine the effect of different cover crop mixtures on corn grain yield, EONR, and economic return, there is a need for long-term studies to determine if results similar to this study continue or change over time.