2020

Intercropping and relay cropping to increase productivity, resilience, and long-term sustainability of corn and soybean cropping systems in Iowa

Swetabh Patel
Iowa State University

Recommended Citation

Patel, Swetabh, "Intercropping and relay cropping to increase productivity, resilience, and long-term sustainability of corn and soybean cropping systems in Iowa" (2020). *Graduate Theses and Dissertations*. 17991.
https://lib.dr.iastate.edu/etd/17991

Intercropping and relay cropping to increase productivity, resilience, and long-term sustainability of corn and soybean cropping systems in Iowa

by

Swetabh Patel

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Crop Production and Physiology

Program of Study Committee:
Andrew W Lenssen, Co-major Professor
Kenneth J Moore
John E Sawyer
Mark A Licht
Shui-zhang Fei

Iowa State University

Ames, Iowa

2020

DEDICATION

I dedicate this dissertation to my mother Suman Singh and my father Shivdas Singh. Without their unconditional support, encouragement, and love for agriculture this aspiration may never have been fulfilled. Your words of motivation kept reminding me the significance of my contribution to science and value of earning an advanced degree.

TABLE OF CONTENTS

LIST OF FIGURES

Page

CHAPTER 2

CHAPTER 3

CHAPTER 4

LIST OF TABLES

Page

CHAPTER 2

CHAPTER 3

CHAPTER 4

ACKNOWLEDGMENTS

I wish to express my deepest and heartfelt gratitude to major professor, Dr. Andrew Lenssen and co-major professor, Dr. Ken Moore, for their relentless guidance and unwavering support through this graduate program. I am extremely grateful to you for providing me the opportunity to pursue my Ph.D. degree. You have facilitated outstanding opportunities that have deeply enriched my graduate experience, understanding of agricultural systems, and scientific competency. My sincere gratitude is also extended to my Committee members, Dr. John Sawyer, Dr. Mark Licht, and Dr. Shui-zhang Fei. For their timely advice and encouragement towards the completion of this program. I am grateful for the generous funding for this dissertation research which was made possible the grant supported by USDA-National Institute of Food and Agriculture-Coordinated Agricultural Program (Award number: 2016-69004-24784).

In addition to learning important professional skills and technical knowhow, I am fortunate to have met wonderful friends at this university, who inspire me to be as passionate about my work as they are about their own – thank you especially to Daniel Kohlhase, Fernando Silva, Matthew Britzmann, Mriganka De, Vaishali Todi, Rajat Sharma and Vishal Mane.

Most importantly, I want to thank my sisters, Parul, Sonu and Rupal, my family and my friends in India for believing in me and encouraging me throughout the process and reminding me that it will all be worth the effort.

ABSTRACT

Soil erosion and nutrient loss as a result of lack of ground cover in conventional corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] cropping systems in the U.S. Midwest warrant use of cover crops to provide improved protection to the soil. There are needs for alternate cropping systems and management practices capable of protecting our resources without sacrificing existing and future crop yield goals. Field pennycress (Thlaspi arvense L.) and winter camelina [Camelina sativa (L.) Crantz] are short season annual oilseed crops having potential to be integrated into corn and soybean systems as cash cover crops. Alfalfa (Medicago sativa L.) also has potential to be intercropped with corn to accelerate its establishment period compared to conventional spring seeding while acting as a cover crop in fall following corn harvest. We interseeded pennycress, camelina and winter cereal rye (Secale cereale L.) in corn and soybean at late reproductive stages. Soybean was relay planted the next year with an objective to (i) determine the effect of cover crops on row crop grain yield, (ii) assess the survival, biomass and seed yield of cover crops, and (iii) determine the effect of cover crops on soil moisture and weed density. In another study corn was intercropped with alfalfa with and without the application of prohexadione with an objective to (i) determine the effect of intercropped alfalfa on corn grain yield, (ii) estimate the survival and biomass production of intercropped alfalfa, and (iii) determine the overall productivity of the intercropping system. Corn and soybean yields were not affected by interseeding cover crops from mid-Aug. to late Sept. but soybean yield when relay planted into oilseed crops was reduced by 12 to 32%. Overall seed yield of pennycress and winter camelina was 218-880 kg ha-1 and 15-770 kg ha-1, respectively. Corn yield was reduced by 23-26% when intercropped with alfalfa in a dry year whereas intercropped alfalfa stand density was reduced by 36-68% in the establishment year.

Despite reduction in corn yield, the overall productivity of a corn and alfalfa intercropping system was greater than the conventional system where alfalfa is spring seeded following corn harvest.

CHAPTER 1. GENERAL INTRODUCTION

Iowa and other upper U.S. Midwest states are known for their capacity to produce high corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] yields (Wright and Lenssen, 2013). The predominant cropping systems in Iowa are corn/soybean and continuous corn with corn and soybean being planted on 5.2 and 4.0 million ha of the 10.6 million ha of total cropland area (USDA NASS, 2019). The choice of crop to be included in the cropping system usually depends on the climate, soil, infrastructure availability, productivity of the crop, market availability, and revenue generated, crop insurance policies, and government subsidies (Greig, 2009). Iowa soils are mostly mollisols, which are very fertile and rich in organic matter and clay (Burras et al., 2020), but due to its extremely cold winters, Iowa has an annual cropping system which is mostly dominated by corn or corn in rotation with soybean (Padgitt et al., 2000). Corn production in monoculture or in rotation with soybean is not necessarily the most environmentally friendly cropping system (Davis et al., 2012) and such monocropping systems driven by crop prices have affected Iowa's soil physical, chemical, and biological properties (Russell et al., 2006), resulting in loss of biodiversity both above and below the soil surface, an increase in soil nutrient loss, and increases in crop vulnerability to various pests, diseases, and weeds (Bartlett et al., 2002; Gassmann et al., 2011; WSSA, 2012). The intensive use of monocropping in Iowa has increased the use of synthetic fertilizers to nourish plants and keep up with the yield goals Excessive use of fertilizers and lack of appropriate agronomic management practices has led to loss of nutrients from the field and export to water bodies like lakes, rivers, and stream leading to creation of a large, annual hypoxic zone in the Gulf of Mexico (USEPA, 2008; IDALS, 2013; Hendricks et al., 2014). Excess use of other synthetic fertilizers has led to problems like soil acidification (Brown and Shrestha, 2000). More than 80% of corn acres planted in Iowa are tilled prior to planting (Wright and Lenssen, 2013). Extensive use of tillage and heavy machinery has led to soil compaction and affected soil properties, plant growth and root development (Unger and Kaspar, 1994; Hamza and Anderson, 2005). Removal of corn stalk/residue for silage, feed, or bedding and fall tillage has resulted in lack of sufficient ground cover causing a disruption in soil nutrient cycling and loss of organic matter (Mann et al., 2002). Removal of crop residue also exposes the soil to increased raindrop impact and reduces water infiltration due to soil erosion. All these factors are responsible for soil erosion occurring at an average rate of 25 Mg/ha/year and is the largest long-term challenge for Iowa (Al-Kaisi, 2002).

Improvement of environmental sustainability of agricultural systems in Iowa and other upper Midwest states requires efforts to properly manage and enhance the quality of soil, water, air, and biodiversity. The problems of unsustainable agricultural systems extend beyond what can be observed or estimated on an individual farm site. If we are to create a prosperous sustainable and resilient agriculture system which is economically vibrant with healthy soil and water, then we need to adopt conservation practices that are economically compelling and easier for farmers and landowners to implement. Current and future challenges require us as a community to think more broadly about the outcomes of agroecosystems and depart from common yield maximizing strategies to increasingly enhance the multiple functions provided by agroecosystems. Diverse cropping systems and adoption of alternative soil and crop management practices such as conservation agriculture that encourage minimum soil disturbance, permanent soil cover and crop rotation, can help alleviate declining soil quality by reducing erosion, compaction, nutrient leaching etc. (Hatfield et al., 2009; Kaspar and Singer, 2011). Farmers should be encouraged to embrace practices such intercropping and leaving more residue on site to aid soil carbon sequestration and thus enhance soil physical and biological properties.

Diversification of cropping systems is an important strategy which can provide many advantages, including improved soil fertility and health, improved efficient nutrient use (Chowdhury and Rosario, 1994), improved control of pests and weeds (Liebman and Dyck, 1993), and improved crop productivity (Gesch et al., 2014). Highly diversified rotations typically avoid proliferation of pests and diseases (Lin, 2011) and could contribute to higher crop production. Moreover, they provide farmers a variety of economic options and avoid the dependence on a single or two crop system. Water use and quality are important topics in Iowa. With respect to water use, alflafa (*Medicago sativa* L.) has a deep and extensive root system, which would make the crop able to collect water and nutrients left in the soil by theprevious crop, such as corn and soybean. Integrating cover crops into the existing crop rotation to break pest and disease cycles can greatly reduce the loads of chemical inputs used for pest management and the amounts that end up in water resources (Sarrantonio and Gallandt, 2003).

There is need for collective farmer effort as the driver of sustainable farming systems for improved soil, water, and air quality. Use of cover crops and alternative farming practices such as intercropping, double cropping, relay cropping, and cash cover crops can help to address some of the challenges that farmers are facing in the Midwest. Some crops are better to grow in rotations in order to have better productivity, better resistance to environmental conditions and pests, and to improve local soil characteristics in the long term. However, sustainable agricultural practices often come at a cost. There is a cost associated with acquiring the necessary machinery and other inputs are needed to make changes for sustainability. Farming is truly a business run for profit and farmers often cannot afford additional costs. Therefore, there is a need is to adopt sustainable practices that have potential to generate additional income to farmers. Practices such as integrating cash cover crops such as field pennycress (*Thlaspi arvense* L.) and winter camelina [*Camelina sativa (*L.) Crantz] and alternate cropping systems like intercropping and relay cropping can address some of these issues and help generate additional income and at the same time protect the environment by making the system more sustainable.

This dissertation includes three separate studies with a purpose to understand the integration of field pennycress, winter camelina, cereal rye, and alfalfa into a corn and soybean cropping system by intercropping and relay cropping. The first two projects studied establishment, green cover, and biomass production of oilseed cover crops pennycress and winter camelina and cereal rye in standing corn and soybean and their subsequent effect on weed community and relayed soybean yield. The third study evaluated intercropping alfalfa along with corn and assessed the stand establishment of alfalfa under a corn canopy as well as its effect on corn grain and aboveground biomass yield. The first two projects were three-year studies conducted in a corn-soybean-corn and soybean-soybean-corn cropping sequence. The second project was also a three-year study with corn intercropped with alfalfa in the first year followed by two years of full alfalfa production.

Outcomes and results of these studies will help to better understand the optimum time of seeding pennycress and camelina in standing corn and soybean as well as the impact of these oilseed cover crops on row crop yield. Research conducted as part of this dissertation will also help understand the opportunity and challenges faced when intercropping alfalfa with.

The monocropping system prevalent in Iowa and U.S. Midwest is not sustainable in the long term and the results and findings of these studies will provide farmers options for improving overall productivity and sustainability by adopting innovative farming practices such as intercropping and relay cropping pennycress, camelina and alfalfa with corn and soybean.

Dissertation Organization

This dissertation consists of five chapters. The first chapter is a general introduction providing a providing an overall description of the research conducted as part of this dissertation. Chapters 2, 3, and 4 are manuscripts describing the efforts and outcomes of the individual studies, with the intention of being published in scientific journals such as Agronomy Journal and Industrial Crops and Products. The titles of the manuscripts are “Integrating and Managing Oilseed Cash Cover Crops in a Corn and Soybean Rotation System”; “Pennycress and Winter Camelina Oilseed Yield and Influence on Row Crops in the Upper Midwest USA” and “Management, Productivity and Weed Community Dynamics in Corn-alfalfa Intercropping in Iowa”. Chapter 5 present general conclusions and provides an overall summary of the individual research studies included in this dissertation.

References

Al-Kaisi, M. 2002. Soil erosion: effect on soil productivity. Iowa State University. IC-488:163 https://crops.extension.iastate.edu/encyclopedia/soil-erosion-effect-soil-productivity (accessed 19 February 2020).

Bartlett, D.W., J.M. Clough, J.R. Godwin, A.A. Hall, M. Hamer, B. Parr-Dobrzanski. 2002. The strobilurin fungicides. Pest Management Science. 58:649-662.

Burras, C.L., G.A. Miller, T.E. Fenton, A. Manu, and J.A. Sandor. 2020. Iowa soil and land use. http://extension.agron.iastate.edu/soils/index.html. (2020 February 24)

Brown, S., and B. Shrestha. 2000. Market-driven land-use dynamics in the middle mountains of Nepal. Journal of Environmental Management. 59:217-225.

Chowdhury, M.K and E.L. Rosario, 1994. Comparison of nitrogen, phosphorous and potassium utilization efficiency in maize/mung bean intercropping. Journal of Agricultural Science. 122(2):193-199.

Davis, A.S., J.D. Hill, C.A. Chase, A.M. Johanns, and M. Liebman. 2012. Increasing cropping system diversity balances productivity, profitability, and environmental health. PloS One. 7:1-8.

Gassmann, A.J., J.L. Petzold-Maxwell, R.S. Keweshan, M.W. Dunbar. 2011. Field Evolved Resistance to Bt Maize by Western Corn Rootworm. PLoS ONE. 6(7): e22629. doi:10.1371

Gesch, R.W., D.W. Archer, and M.T. Berti. 2014. Dual cropping winter camelina with soybean in the northern corn belt. Agronomy Journal. 106(5):1735-1745.

Greig, L. 2009. An analysis of the key factors influencing farmer's choice of crop, Kibamba Ward, Tanzania. Journal of Agricultural Economics. 60:699-715.

Hamza, M.A., and W.K. Anderson. 2005. Soil compaction in cropping systems: A review of the nature, causes and possible solutions. Soil and Tillage Research. 82:121-145.

Hatfield, J.E., L.D. McMullen, C.S. Jones. 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. Journal of Soil and Water Conservation. 64(3): 190-199

Hendricks, N.P., S. Sinnathamby, K. Douglas-Mankin, A. Smith, D.A. Sumner, and D.H. Earnhart. 2014. The environmental effects of crop price increases: Nitrogen losses in the US Corn Belt. Journal of Environmental Economics and Management. 68:507-526.

IDALS. 2013. Iowa nutrient reduction strategy, a science and technology based framework to assess and reduce nutrients to Iowa waters and the Gulf of Mexico. Iowa Dep. Agric. and Land Stewardship, Iowa Dep. Nat. Resour., and Iowa State Univ. Col. of Agric. Life Sci.

http://www.nutrientstrategy.iastate.edu/documents (accessed 21 February 2020).

Iowa State University, Extension and Outreach. Soil and land use. https://www.extension.iastate.edu/soils/crop-and-land-use-statewide-data (accessed 22 February 2020).

Kaspar, T.C., J.W. Singer. 2011. The use of cover crops to manage soil. In: Hatfield, J.L., Sauer, T.J., editors. Soil Management: Building a stable base for agriculture. Madison, WI: American Society of Agronomy and Soil Science Society of America. p. 321- 337.

Liebman, M. and E. Dyck. 1993. Crop rotation and intercropping strategies for weed management. Ecological Applications. 3(1): 92-122.

Lin, B.B. 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. BioScience. 61(3):183-193.

Mann, L., V. Tolbert, and J. Cushman. 2002. Potential environmental effects of corn (Zea mays L.) stover removal with emphasis on soil organic matter and erosion. Agriculture, Ecosystems & Environment. 89:149-166.

Padgitt, M., D. Newton, R. Penn, and C. Sandretto. 2000. Production practices for major corps in U.S. Agriculture, 1990–1997. Resource Economics Division, Economic Research Service, USDA Stat. Bull. No. 969.

http://www.ers.usda.gov/publications/sb969 (accessed 25 February 2020).

Russell, A.E., D.A. Laird, and A.P. Mallarino. 2006. Nitrogen fertilization and cropping system impacts on soil quality in Midwestern Mollisols. Soil Science Society of America Journal. 70:249-255.

Sarrantonio, M., and E. Gallandt. 2003. The role of cover crops in North American cropping systems. Journal of Crop Production. 8:53-74.

Unger, P.W., and T.C. Kaspar. 1994. Soil compaction and root growth: a review. Agronomy Journal. 86:759-766.

USDA. *National Agricultural Statistics Service*. 2019. 2017 Census of Agriculture.

https://www.nass.usda.gov/Publications/AgCensus/2017/#full_report (accessed 21February 2020).

USEPA. 2008. Mississippi River/Gulf of Mexico Watershed Nutrient Task Force Gulf hypoxia action plan 2008 for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico and improving water quality in the Mississippi River basin. USEPA, Washington, DC. http://water.epa.gov/type/watersheds/named/msbasin/upload/2008_8_28_msbasin_ghap2008_update082608.pdf (accessed 21 February 2020).

Weed Science Society of America. 2012. Managing Herbicide Resistant Weeds in Iowa. http://weedscience.org/usa (accessed 20 February 2020).

Wright, D., and A.W. Lenssen. 2013. Recognizing Challenges to Iowa's Annual Cropping Systems. Agric. Environ. Ext. Publ. 186. Iowa State Univ. Ext. and Outreach, Ames, IA.

http://lib.dr.iastate.edu/extension_ag_pubs/186 (accessed 20 February 2020).

CHAPTER 2. INTEGRATING AND MANAGING OILSEED COVER CROPS IN CORN AND SOYBEAN

Swetabh Patel, Andrew W. Lenssen, Kenneth J. Moore

S. Patel, A.W. Lenssen, K.J. Moore, Dept. of Agronomy, Iowa State Univ., Agronomy Hall, Ames, IA 50011-1010, USA.

Modified from a manuscript to be submitted to Agronomy Journal

Abstract

Winter camelina [Camelina sativa (L.) Crantz] and field pennycress (Thlaspi arvense L.) are short season annuals which can be harvested for oilseed and can be an alternative choice of cover crop to be integrated into corn (Zea mays L.) and soybean [Glycine max (L.) Merr.] rotations in the northern Corn Belt, USA. However, successful establishment of these cover crops in standing corn and soybean is contingent upon the right timing of their interseeding. Therefore, a field study was started in Ames, IA in 2016 to evaluate cereal rye (Secale cereale L.), field pennycress (PC) and winter camelina (WC) fall and spring stand density, biomass yield, green cover and their effect on corn and soybean yield when broadcast interseeded at R4, R5 and R6 reproductive stages in corn and R6, R7 and R8 stages in soybean. Interseeding cover crops did not reduce corn or soybean yield. Overall, cover crop fall and spring stand densities and biomass yield were affected by interseeding date. Late interseeding improved the survival and biomass production of oilseed cover crops. Oilseed cover crop biomass in fall was less than 50 kg ha-1. Rye produced the greatest biomass (2314 kg ha-1) averaged across all seeding dates when interseeded in corn. Overall cover crops provided less than 10% green cover in fall whereas in spring rye and pennycress provided up to 41 and 22% green cover, respectively. Both rye and pennycress successfully lowered weed density in spring. Interseeding of pennycress and

camelina in corn and soybean did not provide as much cover as rye and should not be planted under dry soil conditions.

Key words: camelina, pennycress, corn, soybean, interseeding, cover crop

Abbreviations: LAI, leaf area index

Introduction

Corn and soybean are major crops in the northern Corn Belt, USA. Corn and soybean are grown on 50.30% and 38.1%, respectively, of the planted crop area in Iowa (USDA NASS, 2019). Corn and soybean together contribute over $14 billion USD in value to the economy of the state of Iowa (USDA-NASS, 2019). While both these crops are highly productive, there are unintended environmental consequences from their production as monocultures. The most serious environmental problem is lack of soil cover over the winter due to residue removal, nominal postharvest residue, the use of fall tillage, and the absence of growing plants (Vetsch and Randall, 2004; Sindelar et al., 2017). Limited or no soil cover can increase the risk of soil erosion and nitrate leaching, decrease soil microbial activity, and decrease soil carbon (Karlen and Doran, 1991; Reddy et al., 2003; Speddinga et al., 2004). Integrating cover crops into corn-soybean systems has potential to offset those unintended negative consequences. Cover crop adoption can offer several benefits such as improving agricultural sustainability through temporal intensification (Gesch and Johnson, 2012), providing soil cover, preventing loss of nutrients, alleviating surface soil loss and decreasing weed pressure (Dabney et al., 2001; Kasper et al., 2001; Sainju et al., 2002; Dhima et al., 2006).

Regardless of proven benefits from cover crops, the total cover crop area in Iowa are still far below the 12.5 million-acre target recommended by IDALS (2013). Although the adoption of cover crops is low, many producers (71 to 80%) believe the addition of cover crops improves soil (Singer et al., 2007; Singer, 2008). Producers have expressed concern regarding lack of time following corn and soybean harvest as a reason for low adoption of cover crops. However, the use of winter annual species broadcast seeded into standing corn and soybean before harvest may represent an opportunity to successfully establish cover crops before freezing conditions occur.

Winter cereal rye (*Secale cereale* L.) is the winter annual cover crop most commonly used in Iowa, representing 87% of the total cover crops planted. Typically, winter rye is grown either for winter soil cover and then terminated in the spring or harvested as forage in the spring and used as livestock feed. Unless used as livestock feed, there is no economic benefit from growing a cereal rye cover crop.

The use of dual-purpose (used as cover crop and can also be harvested for oilseed) winter annual oilseed cover crops such as winter camelina [*Camelina sativa* (L.) Crantz.] and pennycress (*Thlaspi arvense* L.) is a potential alternative to cereal rye. Winter camelina and field pennycress are both winter hardy and can provide ecological benefits such as protection from soil erosion, N and P scavenging (Ott et al., 2015), and provisions for pollinators (Eberle et al., 2015). Moreover, these winter annual oilseeds can be harvested for seed while allowing options for double- and relay-cropping with soybean (Gesch and Archer, 2013; Gesch et al., 2014). Relay-cropping soybean into growing camelina was shown to be an economically viable system when the camelina is direct seeded in the fall following wheat (Gesch et al., 2014). The oil extracted from winter camelina and pennycress has economic value as a biofuel (Keske et al., 2013). In addition, camelina oil can also be used for human and animal consumption (Berti et al., 2016) and its meal is approved by FDA as feed for poultry and ruminant livestock (Fan and Eskin, 2013). Incorporating these winter annual oilseeds into corn-soybean rotations offers producers a chance to intensify production while balancing the needs of producing food, feed, and fuel without displacing the important cash crops of the region.

Identifying the optimum broadcast seeding time for winter annual cover crops into corn and soybean is a key to enabling successful adoption of these crops and to improve the ecosystem services provided by corn and soybean rotations. Therefore, a multi-year experiment consisting of several broadcast seeding timings was established. The objectives of this study were to: 1) evaluate establishment and survival of broadcast interseeded winter annual cover crops at later growth stages of corn and soybean, and 2) determine the effects of interseeding cover crops on the weed community and density, and 3) determine the impact of broadcast interseeded winter annual cover crops on corn and soybean yield and quality.

Materials and Methods

Site Description

A 3-yr field study was started in 2016 near Boone, Iowa (42°0'40.92"N 93°44'38.06"W) in two different crop sequences (corn-soybean-corn and soybean-soybean-corn). The entire study was replicated in 2017 at a nearby but separate site. The soil were Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) and Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll). The soils were moderately well drained to poorly drained. Weather data for monthly mean temperature and total precipitation for the study sites and years were collected from weather stations located near the study site and reported by the Iowa Environmental Mesonet Network (Herzmann, 2020). Soil test P and K levels were maintained according to the Iowa State recommendation for corn and soybean on the basis of soil testing (Mallarino et al., 2013) (Table 1).

Experimental Design and Treatments

The experimental design was a split plot with four replications. The main plot (9.1 m x 7.6 m) was three dates of cover crop seeding corresponding to R4, R5 and R6; and R6, R7 and R8 developmental stages in corn (Abendroth et al., 2011) and soybean (Wright and Lenssen, 2013), respectively. The subplots (3.0 m x 7.6 m) were planted with three different cover crops (pennycress, winter camelina and cereal rye) seeded into either standing corn or soybean in the first year of the sequence. Each replication had an additional control plot with no cover crop. Each year adapted corn hybrid (DeKalb DKC57-75RIB) and soybean variety (Asgrow 2663) were seeded in rows spaced 76-cm apart and managed using practices common to the region where the experiment was conducted. Pre-plant fertilizer was applied along with pre- and post-emergent herbicides. Weeds were controlled according to need within each site (Table 1). Planting dates of corn, soybean, and cover crops as well as management practices are shown in Table 1.

Planting and Agronomic Management

Corn/soybean planting and harvest

In the first year corn-soybean-corn sequence, a regionally adapted corn hybrid (DeKalb DKC57-75RIB) was planted (8 PLS m^{-2}) using a four-row planter. At the time of corn planting 168 kg N ha^{-1} was broadcasted as urea. In the first year of soybean-soybean-corn sequence, a typical variety (Asgrow 2663) of soybean was planted at 45 PLS m^{-2}. According to soil tests these sites were low in available P and K. Therefore, a fertilizer blend consisting 123 kg P ha^{-1} and 112 kg K ha^{-1} in the forms of diammonium phosphate and muriate of potash, respectively, was also applied at the time of corn and soybean planting to adjust soil available P and K levels. Grain yield for both corn and soybean were determined by harvesting the two center rows using a plot combine. Corn and soybean yields were adjusted and reported at 155 and 130 g kg^{-1} moisture, respectively.

Cover crop seeding and data collection

Cover crops were interseeded in each block in a split-plot arrangement at the three reproductive growth stages of corn and soybean (Table 1). Pennycress (line MN106), winter camelina (cv. Joelle) and cereal rye (cv. Rymin) were hand-broadcast in between the standing corn and soybean rows at 1064, 1368 and 222 PLS m^{-2}. Seeds were then lightly raked to mix with soil and increase seed-soil contact for better germination. No cover crop was seeded in the control plots. At each cover crop seeding, corn and soybean leaf area index (LAI) was measured using a Decagon AccuPAR leaf area meter (Decagon Devices Inc., Pullman, WA). Four LAI measurements on a sunny day with clear sky were taken diagonally across the center two rows and averaged to calculate the LAI per plot. In the spring of the second year of both crop sequences, a fertilizer blend (78:34:34 kg ha^{-1}, N:P:K) was broadcast applied only to the pennycress and winter camelina plots at bolting stage to increase the growth and seed yield of the oilseed crops. Later, the rye cover crop was killed using glyphosate [N-(phosphonomethyl)glycine] at least 2-4 days before planting soybean.

Several metrics were used to assess the establishment and survival of cover crops. Soon after germination following each seeding time in the corn and soybean, cover crops were counted from two marked 0.25 m^2 in the center of each plot to determine the establishment density. Later in the fall, prior to freeze-up, cover crops were assessed for survival by counting the total number of cover crop plants from the same marked areas used earlier for determining cover crop establishment. A cover crop survival index was calculated as a ratio of cover crop plant density before freeze up (cover crop survival) and density soon after germination (cover crop establishment).

Survival Index (SI) = survival density (plants m^{-2}) / establishment density (plants m^{-2}). [Eq.1] In the fall before freeze-up and in spring at the time of rye termination before planting soybean, cover crop (rye, pennycress, and camelina) aboveground biomass samples were collected by hand harvest from two 0.76 m^2 areas between the center two rows of each plot.

Harvested aboveground biomass of cover crops was dried in a forced air oven at 60 °C until reaching a constant weight and then weighed to calculate the aboveground biomass weight per hectare. The cover crop establishment was also assessed using the percentage of green cover produced by the growing cover within each plot. To determine green cover in the fall (before freeze up) and spring (at rye termination), two photos were taken from within each plot in the center row with a camera set at 1 m above the soil surface. The photos were then assessed using the Canopeo application developed by Patrignani and Ochsner (2015) with the default settings. The average green cover was calculated for each plot by averaging the percent green cover from each of the two photos.

Soil Sampling and Analysis

Baseline soil samples from 0-15 and 15-60 cm for nutrient analyses were collected at the start of each study. Soil moisture samples from all the treatments were collected using a hand push probe (1.7 cm diameter, JMC Soil Samplers, Newton, IA, USA) at the time of rye cover crop termination in spring to see the effect of cover crop on soil moisture concentration. Samples were composited from three random spots within the center two rows of each plot. Soil samples for moisture analysis were weighed at field moist condition and then dried at 105 °C until a constant weight was reached and then weighed to calculate gravimetric soil moisture concentration on a dry weight basis.

Weed Data Collection

Weed count data from all the plots were collected in spring at the time of rye termination. Total number of weeds within 0.1-m^2 were counted from five random locations in each plot within a circular quadrant. Weed density for each weed species and total weed density m^{-2} was calculated by multiplying by a factor of two.

Statistical Analysis

Data from interseeding in corn-soybean-corn and soybean-soybean-corn sequences were analyzed separately. For each system, a combined analysis of variance was performed using PROC GLIMMIX in SAS version 9.4 (SAS Institute, 2014). Environment (year × location), and treatments were considered fixed while blocks nested within environment was considered random. Due to significant environment × treatment interaction, data were analyzed separately for each year within each cropping sequence considering treatments as fixed and block as random. Since the treatment structures of the experiments were incomplete factorials, contrast statements were used for comparing treatments and individual mean comparisons were made at $\alpha = 0.05$. Microsoft Excel was used to perform regression analysis between fall survival of cover crops and leaf area index (LAI) at interseeding.

Results and Discussion

Weather Conditions

The 2016 growing season (May-Dec.) was warmer than the 30-year mean temperature. A deviation of greater than 2 °C was observed in June and Sept 2016, while the temperatures in Oct and Nov were 3 and 5 °C above the 30-year mean (Fig 2). While temperatures were above average during the 2016 growing season, total precipitation (May-Dec) was 7-cm above the long-term mean. Excess precipitation occurred in the months of Aug and Sept while June received 10-cm less rainfall compared to the long-term mean.

The 2017 growing season was also warmer with mean temperatures in the month of Sept being 2 °C above 30-year, respectively. While temperatures were warmer in 2017, the total seasonal precipitation was well below the long-term mean. Most of the months in 2017 were drier than normal, especially from June through Sept which received 25-cm rainfall below average. The month of Oct received an excess of 9 cm precipitation while Nov and Dec precipitation was below average.

The growing season temperatures in 2018 was similar to the long-term means with deviations less than 1 °C (Fig. 1). Overall, slightly cooler temperatures were recorded from Jan through Apr and in the month of Nov whereas May and Dec were 4 and 2 °C warmer than the long-term mean. Meanwhile, an excess precipitation of 36-cm compared to the 30-yr mean was recorded throughout the growing season in 2018. Excessive precipitation was received particularly in the months of June (15-cm), Aug (9-cm), Sept (9-cm) and Oct (6-cm)

Corn and Soybean Seed Yield, Seed Quality, and Soil Moisture

Overall, corn grain yield was greater in 2016 than in 2017 regardless of experimental treatments. There was no effect of interseeding the cover crops or seeding date on corn grain yield in either year where cover crops were interseeded into standing corn (Table 2). The average corn grain yield across all treatments was 13.7 and 12.2 Mg ha^{-1} in 2016 and 2017, respectively. Corn seed protein, oil and starch concentrations were not affected by intercropping, and averaged 77.5, 41.2, and 738 g kg^{-1} in 2016 and 67.5, 34.1, and 703 g kg^{-1} in 2017, respectively. Lower grain yield and seed quality in 2017 were likely due to below average precipitation in the growing season of 2017 (Fig. 1) and thus lower soil moisture availability for the crop.

Soybean seed yield and seed protein, oil and fiber concentrations followed a similar trend as for corn and were not affected by cover crop species or seeding date (Table 3). Similar findings were reported in a multilocation trial conducted by Patel et al. (2019) where a rye cover crop interseeded into standing soybean at leaf drop stage did affect soybean seed yield. The average soybean yield was 4.05 Mg ha^{-1} in 2016 and 3.5 Mg ha^{-1} in 2017. In 2016 soybean seed oil, protein, and fiber concentrations across all the treatments were 342, 185 and 48 g kg^{-1} whereas, in 2017 these concentrations averaged to be 327, 175 and 42 g kg^{-1}, respectively. These results indicate that interseeding cover crops at late corn and soybean reproductive stages is possible without affecting the seed quality and yield of the corn and soybean.

Overall, soil moisture in the top 60 cm was either similar or greater in spring (of the year following the fall cover crop interseeding) than in the fall (Tables 4 and 5). Interseeded cover crops growing with corn and soybean row crops may reduce the soil moisture in the fall as well in the following spring. However, results in our study show that fall and spring moisture in 0-30 and 30-60 cm of topsoil surface was not affected by interseeding cover crops into standing corn or soybean.

Cover Crop Establishment

Stand density and survival

When interseeded into corn, survival stand density of the cover crops in the fall was influenced by cover crop species and its interaction with different seeding dates (Table 6) Overall fall survival of cover crops was low in both the seeding years 2016 and 2017. Greatest fall stand survival of camelina in 2016 (498 plant m^{-2}) and 2017 (226 plant m^{-2}) was achieved when interseeded at the R6 growth stage of corn. Pennycress on the other hand had greater fall stand survival when interseeded at R5 (369 plants m^{-2}) and R6 (277 plants m^{-2}) in 2016 and 2017, respectively. Unlike pennycress and camelina, fall stand density of rye was not affected by seeding date and averaged 158 and 125 plants m^{-2} in 2016 and 2017, respectively.

Cover crop stand density in the spring was lower compared to fall for all the cover crop species indicating some plants were winter killed. For 2016 interseeding, cover crop species and seeding date had significant effects on spring stand density whereas in 2017, the interaction of cover crop species and planting date influenced the spring stand density for interseeded cover crops. Pennycress had the highest stand density (151 plants m^{-2}) across all the seeding dates in 2016 whereas highest stand density across all cover crop species was achieved when cover crops were interseeded at the later seeding date (R6). For 2017 interseeding, higher spring stand density was achieved at later seeding dates for pennycress (R5 and R6) and rye whereas camelina stand density was not affected by seeding date.

Similar to interseeding in corn, fall stand density of cover crop species interseeded in standing soybean varied with seeding date (Table 7). For the 2016 interseeding in soybean, pennycress seeded at R8 had the highest stand density (515 plants m^{-2}) across all the treatments. Fall stand density of winter camelina in 2016 was maximized (205 plants m^{-2}) when seeded at the latest seeding date (R8). Unlike pennycress and camelina, fall stand density of rye cover crop was not affected by the seeding date. In 2017, fall stand density was greater at later seeding dates for camelina (R8) and rye (R7 and R8). Conversely, there was no effect of seeding date on stand density of pennycress.

Spring stand density of cover crops interseeded in soybean was affected by cover crop species and seeding date in 2016 whereas an interaction of cover crop species with seeding date was present for spring stand density in 2017 (Table 7). In 2016, earlier seeded (R6) cover crops had the lowest spring stand density. Across all seeding dates, pennycress had higher spring stand density compared to camelina. Spring stand density for 2017 interseeding was similar across all the cover crop species seeded at R8 whereas camelina and rye seeded at early seeding dates had the lowest stand density.

Cover crops when interseeded in standing corn and soybean may or may not germinate depending upon topsoil moisture and weather conditions, especially having adequate precipitation. However, cover crop seedlings after germination may die due to unfavorable conditions such as lack of enough sunlight under the corn and soybean canopy. The final stand count of cover crops in the fall represents the final survival following establishment. Survival index of pennycress (2.77) seeded at R4 in corn was highest in 2016 whereas in 2017 highest SI was for the pennycress (3.35) seeded at R5 (Table 6). An SI greater than 1 for pennycress can be explained by the inherent seed dormancy in pennycress (Saini et al., 1987; Karimmojeni et al., 2014; Kevin et al., 2015) which may cause delayed germination in an unfavorable environmental condition. In soybean interseeding, SI was affected by seeding date in 2016 and cover crop species in 2017 (Table 7). In 2016, the SI of cover crops in soybean were lower if interseeded at R6 compared to R7 or R8 stages, indicating low survival probability of earlier seeded cover crops. Whereas in 2017, camelina across all the seeding dates had lowest chances of survival due to low SI compared to pennycress and rye.

Lack of sufficient photosynthetically active radiation (PAR) under the corn and soybean canopy can influence germination, initial establishment and subsequent survival of interseeded cover crops (Crusciol et al., 2013; Wilson, 2013; Bich et al., 2014; Belfry and Van Eerd, 2016; Geiszler, 2018). There was a curvilinear relationship between the late fall survival density of camelina and the corn LAI at the time of interseeding in 2016 ($R^2 = 0.847$) and 2017 ($R^2 = 0.497$) (Fig. 2). For camelina the R^2 value implies that more than 80 and 49% of variation in fall survival of camelina can be explained by corn LAI at interseeding. This suggests that interseeding camelina in corn with a dense canopy reduced the survival of camelina plants in the fall. Rye was unaffected by LAI at the time of interseeding in corn. Conversely, in 2017, there was a weak relationship for LAI at seeding predicting late fall stand density for pennycress ($R^2 = 0.336$).

In both seeding years, camelina fall stand density increased when interseeded in soybean with a less dense canopy whereas the fall survival was progressively decreased with increasing soybean LAI at the time of interseeding (Fig. 3). In 2016, pennycress fall survival density followed the same trend as camelina. However, in 2017, pennycress fall stand density increased when seeded in soybean at higher LAI. In 2017, there was an extended period of dry weather (Fig. 1) after first (R6) and second (R7) seeding dates of cover crops which may have caused the pennycress seeds to germinate later when rainfall and moisture became sufficient (Royo-Ensal et al., 2015). Unlike pennycress and camelina, rye fall stand density decreased when interseeded either early (high LAI) or later (low LAI) in soybean.

These results suggest that seeding oilseed cover crops in corn and soybean under a dense canopy with low sunlight penetration may result in poor stands in late fall and the subsequent spring. Therefore, for achieving successful stands of pennycress and camelina cover crops interseeding in corn and soybean should be delayed to near crop harvest.

Aboveground biomass

Fall aboveground biomass of cover crops interseeded in corn was affected by the interaction of cover crop species and interseeding date in 2016 whereas in 2017, fall biomass was only affected by cover crop species. (Table 6). Rye interseeded at earlier seeding dates in 2016 produced the highest amount of biomass (298 kg ha^{-1}) in the fall whereas pennycress and camelina produced 74 and 22 kg ha^{-1} total biomass, respectively, across all the seeding dates. In 2017, rye had the highest fall biomass (143 kg ha^{-1}) compared to pennycress (27 kg ha^{-1}) and camelina (20 kg ha^{-1}). Fall biomass of cereal rye produced in our study was greater than the amount reported in a study conducted in Minnesota by Noland et al. (2018) where rye was interseeded in corn at V7 stage. However, similar pennycress and camelina fall biomass were reported in a study conducted by Noland et al., (2018) and Geiszler (2018) in North Dakota.

Fall aboveground biomass of cover crops interseeded in soybean was affected by cover crop and seeding date in 2016, however, in 2017 the interaction of cover crop by seeding date influenced fall aboveground biomass (Table 7). Similar to interseeding in corn, rye in 2016 had highest amount of fall biomass across all cover crop species when interseeded in soybean. Mean rye biomass across all seeding dates in fall 2016 was 246 kg ha^{-1} whereas pennycress and camelina accumulated 67 and 32 kg ha^{-1} biomass across all seeding dates. In 2016, the highest amount of fall biomass across all the cover crops was produced when interseeded at R7 stage in soybean. In 2017, cereal rye interseeded at R7 produced the highest amount of biomass (164 kg ha^{-1}) across all the treatments.

In both seeding years, 2016 and 2017, total spring biomass accumulation when cover crops were interseeded in corn was significantly different among the cover crop species and not affected by seeding date or its interaction with cover crop (table 6). Cereal rye produced the greatest amount of spring biomass in 2016 (3310 kg ha^{-1}) and 2017 (1318 kg ha^{-1}) compared to pennycress and camelina across all the seeding dates. Across seeding dates, pennycress and camelina accumulated 784 and 215 kg biomass ha^{-1} in spring (at rye termination) when interseeded in 2016 and 139 and 104 kg ha^{-1}, when interseeded in 2017, respectively. Spring biomass of camelina in our study was low compared to previous study conducted in Iowa where camelina was seeded after soybean harvest (Appelgate et al., 2017). Lower spring biomass production of cover crops interseeded in 2017 can be explained by low precipitation in summer and fall of that year (Fig. 1).

When interseeded in soybean, spring biomass of cover crops was only affected by the cover crop species in 2016 whereas in 2017, interaction of cover crop and seeding date had significant effect on spring biomass accumulation (Table 7). Cereal rye interseeded in 2016 produced the highest amount of spring biomass (1777 kg ha^{-1}) across seeding dates as compared to pennycress and camelina. In a study conducted in Iowa where rye was interseeded in soybean at leaf drop stage, Patel et al. (2019) reported a lower rye biomass yield of 930 kg ha^{-1} when rye was terminated in spring before planting row crop. Pennycress and camelina produced 851 and 397 kg ha^{-1} spring biomass across all seeding dates when interseeded in 2016. Rye seeded at later seeding dates (R7 and R8) produced the highest amount of spring biomass (1404 kg ha^{-1}) compared to all the treatments. While camelina spring biomass was maximized (444 kg ha^{-1}) when interseeded at the later seeding date (R8), pennycress biomass did not differ with seeding date and averaged 348 kg ha^{-1}. These results indicate that irrespective of cover crop stand density in fall, cereal rye accumulated greater biomass in spring than pennycress or camelina when interseeded in corn or soybean.

Green cover

One of the benefits of interseeding cover crops in standing corn and soybean is that it provides more time for cover crop establishment and growth in fall and thus provides more protective cover to the soil before freeze up (Noland et al., 2018). Fall green cover following corn harvest varied with cover crop species and their interaction with seedign date. Rye cover crop interseeded at R5 provided the highest amount of cover (32.5%) in fall 2016. Later interseeding of camelina provided more cover compared to earlier seeding whereas pennycress had no effect of seeding date on fall cover. Dry summer and fall conditions in 2017 reduced the fall cover when cover crops were interseeded in corn. Rye interseeded in corn in 2017 had the highest cover (8.1%) whereas cover provided by pennycress (3%) and camelina (0.8%) was very low.

Fall cover in soybean were affected by cover crop species and seeding date in 2016. However, in 2017 there was no effect of cover crop species or seeding date on fall cover. Lack of a treatment effect on fall cover in 2017 was due to low overall cover crop establishment in response to dry soil conditions (Fig. 1). Rye in 2016 provided 1.6 and 1.8 times more ground cover compared to pennycress and camelina, respectively. Greater fall cover was also provided when cover crops were seeded at R7 stage in soybean.

Winter hardy cover crops interseeded in standing corn and soybean should overwinter, resume active growth in spring, and protect the soil by providing green cover (Dabney et al., 2001). Green cover in spring was significantly affected by main effect of cover crop species in 2016 and 2017. For 2016 interseeding, rye provided two and four times more cover in spring compared to pennycress and camelina, respectively. Whereas across all seeding dates, pennycress provided more than twice spring cover as compared to camelina when interseeded in corn. Rye interseeded in 2017 provided 55% spring cover, significantly higher than the cover provide by pennycress (10%) and camelina (4%).

In soybean, spring cover was significantly affected by cover crop species and seeding date in 2016 whereas interaction of cover crop and seeding date had significant effect on spring cover in 2017. In 2016, later seeded (R8) cover crops provided more spring cover compared to early seeding (R6) whereas across seeding dates rye provided greater spring cover (45%) compared to pennycress (27%) and camelina (15%). In 2017, rye interseeded in soybean at later seeding dates (R7 and R8) had the highest spring cover (51%) whereas cover of pennycress was maximum when seeded at later seeding date (R8).

Overall lower green cover and biomass production in fall compared to spring when cover crops were interseeded in corn and soybean suggests that most of the benefits of integrating a cover crop are provided in spring rather than in fall. Rye can maintain active growth at very low temperatures which can extend the growing period for rye in fall. Greater green cover in fall and spring indicates a more vigorous growth pattern and ability of rye to produce more biomass in a short period of time. Previous studies have shown that rye roots harbor corn seedling pathogens and may elevate seedling diseases in corn following a rye cover crop (Bakker et al., 2016; Acharya et al., 2020). Thus, adoption of cereal rye as a preferred cover crop when preceding soybean should be promoted to farmers.

Weed Community and Distribution

When cover crops were interseeded in corn in 2016 and in 2017, the weed density at the time of rye termination in the following spring was significantly affected by the type of cover crop and seeding date (Table 8). Interseeded cereal rye and pennycress both significantly lowered the spring weed density following corn harvest. Mean weed density in rye, pennycress, and camelina treatments across all seeding dates were 8, 18 and 50 plants m^{-2}. Spring weed density was successfully reduced by 91% and 80% by rye and pennycress compared to the no cover crop control treatment following corn harvest in 2016. Rye and pennycress interseeded in corn in 2017, reduced weed density in following spring by 58 and 39%. Overall spring weed density was low following corn harvest in 2017. The low weed density in 2018 spring was likely a result of below normal precipitation in summer and fall of 2017 (Fig. 1).

Similar to corn, spring weed density following soybean harvest in 2016 was affected by type of cover crop species and seeding date (Table 8). However, in spring following 2017 soybean harvest weed density was not affected by cover crop species, seeding date, or their interaction. Absence of a cover crop effect on spring weed density following 2017 soybean harvest may be explained by overall low weed recruitment and low cover crop stand and biomass in spring 2018 (Table 7).

The spring weed community following 2016 corn harvest consisted of 94% broadleaf and 6% grass species. Broadleaf weed species, included Canadian horseweed [*Conyza canadensis* (L.) Cronquist] 972%), West Indian nightshade (*Solanum ptychanthum* Dunal.) (14%), and dandelion (*Taraxacum sp.* L.) (12%). The remaining 2% of observed broadleaf weeds was composed of four other species. Among grass weeds, giant foxtail (*Setaria faberi* Herrm.) and witchgrass (*Panicum capilare* L.) consisted of 58 and 40%, respectively.

Spring weed community following the 2017 corn harvest included 92 and 8% of broadleaf and grass weed species, respectively. Major broadleaf weeds were tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] (27%), West Indian nightshade (23%), dandelion (13%), little hogweed (*Portulaca oleracea* L.) (13%), lambsquarters (*Chenopodium album* L.) (9%) and 15% from five other species.

Following the 2016 soybean harvest, the spring weed community consisted of 84% broadleaf and 16% grass weed species. Most common broadleaf species were Canadian horseweed (73%), dandelion (9%), tall waterhemp (7%), creeping woodsorrel (*Oxalis corniculata* L.) (5%), and 6% from three other species. Some major grass weed species were witchgrass (68%), giant foxtail (24%), barnyardgrass [*Echinochloa crus-galli* (L.) P. Beauv.] (4%), yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.] (1%), and crabgrass (*Digitaria* sp. L.) (3%).

Spring weed community following 2017 soybean harvest included Canadian horseweed (58%), dandelion (11%), white clover (*Trifolium repens* L.) (11%), tall waterhemp (7%), witchgrass (4%) and 9% four other species. The total weed community was represented by 96% broadleaf and 4% grassweed species.

In our study, improved stand density and higher biomass accumulation of cover crops when interseeded later in corn and soybean resulted in better suppression of weeds in the spring. Rye was most effective in reducing weeds in spring following corn and soybean harvest. Our findings agree with previous research where growing rye plants or decomposing biomass effectively controlled weeds (Putnam et al., 1983; Schulz et al., 2013). Allelochemicals (allyl isothiocyanate and allyl thiocyanate) present in pennycress seeds and other brassicaceous species have been shown to effectively control weeds when applied to soil (Haramoto and Gallandt, 2004; Vaughn et al., 2005; Isbell 2009). Overall maximizing spring biomass production of cover crops would effectively suppress at least some weeds in corn-soybean systems.

Conclusions

Interseeding cover crops at later reproductive stages of standing corn and soybean did not affect the row crop yield. In general oilseed cover crops had better survival and biomass production when interseeded in soybean than in corn. Earlier interseeding of oilseed cover crops (pennycress and camelina) in corn (R4 and R5) and in soybean (R6 and R7) had low survival in the fall. Low oilseed cover crop fall survival was likely an effect of reduced PAR under the corn and soybean canopy at the time of interseeding. Biomass and green cover of cover crops in fall was low in both corn and soybean with rye producing the greatest amount of biomass. Pennycress and camelina spring biomass were maximized when interseeded at later (closer to harvest) in corn and soybean. In general, camelina and pennycress produced more spring biomass when interseeded in soybean whereas rye accumulated greater spring biomass when interseeded in corn. Although available soil moisture at time of interseeding was not measured, interseeding in a dry year led to an overall decreased fall and spring cover crop biomass and green cover, indicating an effect of low moisture availability at the time of and following interseeding which prevented rapid establishment. There was lack of a cover crop effect on soil moisture in the top 60 cm in fall and spring possibly due to overall low establishment, transpiration, and biomass production of the cover crop. Rye, along with pennycress, successfully reduced weed density in spring by 50-90% and 40-80%, respectively. We suggest avoiding interseeding of pennycress and camelina into dense corn and soybean canopies to increase the chances of survival and subsequent growth in fall and spring. This research was conducted for two years and has raised questions that require further investigation, including changes in management such as post-harvest broadcast and drilling, and breeding for drought and shade tolerant lines of pennycress and camelina. Findings of our study indicate that pennycress has potential for use as an interseeded cover crop, however, with currently available cultivars of pennycress and camelina, interseeding in corn and soybean should not be recommended in Iowa.

Acknowledgments

This research was supported by a grant funded by USDA-National Institute of Food and Agriculture-Coordinated Agricultural Program (Award number: 2016-69004-24784). We are grateful for field and technical support provided Agricultural and engineering farm research crew, hourly undergraduates, and Assistant Scientist Roger Hintz.

References

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. Publ. PMR-1009. Iowa State Univ. Ext. https://store.extension.iastate.edu/product/Corn-Growth-and-Development. (accessed 20 February 2020)

Acharya, J., T.B. Moorman, T.C. Kaspar, A.W. Lenssen, and A.E. Robertson. 2020. Cover Crop Rotation Effects on Growth and Development, Seedling Disease, and Yield of Corn and Soybean. Plant Disease. 104(3):677-687.

Bakker, M.G., J. Acharya, T.B. Moorman, A.E. Robertson, and T.C. Kaspar. 2016. The potential for cereal rye cover crops to host corn seedling pathogens. Phytopathology. 106(6):591-601.

Belfry, K.D., and L.L. Van Eerd. 2016. Establishment and impact of cover crops intersown into corn. Crop Sci. 56:1245-1256.

Berti, M.T., R.W. Gesch, C. Eynck, J. Anderson, S. Cermak. 2016. Camelina uses, genetics, genomics, production and management. Ind. Crops Prod. 94:690-710. doi:10.1016/j.indcrop.2016.09.034

Bich, A.D., C.L. Reese, A.C. Kennedy, D.E. Clay, and S.A. Clay. 2014. Corn yield is not reduced my mid-season establishment of cover crops in Northern Great Plains environments. Crop Manage. 13(1). doi: 10.2134/CM-2014-0009-RS.

Crusciol, C.A.C, A.S. Nascente, G.P. Mateus, E. Borghi, E.P. Leles, and N.C.B. Santos. 2013. Effect of intercropping on yields of corn with different relative maturities and palisadegrass. Agron. J. 105:599-606.

Fan, L. and N.M. Eskin. 2013. Camelina oil: chemistry, properties and utilization. Recent Res. Devel. Lipids. 9(1):25-137.

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221–1250. doi:10.1081/CSS-100104110

Dhima, K.V., I.B. Vasilakoglou, I.G. Eleftherohorinos, and A.S. Lithourgidis. 2006. Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop Sci. 46:345–352. doi:10.2135/cropsci2005-0186

Geiszler, M.M., 2018. Interseeding Cereal Rye and Winter Camelina into Corn in North Dakota (Doctoral dissertation, North Dakota State University).

https://pdfs.semanticscholar.org/f53f/3b3978e51c3f0137ade6626f4582e90b822e.pdf (accessed 18 March 2020)

Gesch, R.W. and J.M-F. Johnson. 2012. Water use in camelina-soybean dual cropping systems. Agron. J. 107:1098-1104. doi:10.2134/agronj14.0626

Gesch, R.W., and D.W. Archer. 2013. Double-cropping with winter camelina in the northern Corn Belt to produce fuel and food. Ind. Crop Prod. 45:248-252.

Gesch, R.W., D.W. Archer, M.T. Berti. 2014. Dual cropping winter camelina with soybean in the northern Corn Belt. Agron. J. 106:1735-1745. doi:10.2134/agronj14.0215

Haramoto, E., E. Gallandt, E. 2004. Brassica cover cropping for weed management: A review. Renew. Agric. Food Syst. 19(4):187-198. doi:10.1079/RAFS200490

Herzmann, D. 2020. Iowa environmental mesonet. Iowa State Univ., Ames, IA. https://mesonet.agron.iastate.edu/climodat/index.phtml?network=IACLIMATE&station=IA0200&report=17 (accessed 20 February 2020).

IDALS. 2013. Iowa nutrient reduction strategy, a science and technology based framework to assess and reduce nutrients to Iowa waters and the Gulf of Mexico. Iowa Dep. Agric. and Land Stewardship, Iowa Dep. Nat. Resour., and Iowa State Univ. Col. of Agric. Life Sci. http://www.nutrientstrategy.iastate.edu/documents (accessed 22 Feb. 2020).

Isbell TA, Cermak SC, Dierig DA, Eller FJ, Marek LF (2015) Registration of Katelyn Thlaspi arvense L. (pennycress) with improved nondormant traits. J Plant Regist. 9:212–215. https://doi.org/10.3198/jpr2014.08.0053crg

Karlen, D., and J. Doran. 1991. Cover crop management effects on soybean and corn growth and nitrogen dynamics in an on-farm study. Am. J. Alt. Agric. 6:71-82. doi:10.1017/S0889189300003891

Karimmojeni H.T., A.R. Taab, B.A.H. Bazrafshan. 2014. Dormancy breaking and seed germination of the annual weeds Thlaspi arvense, Descurainia sophia and Malcolmia africana (Brassicaceae). J. Plant Protect. Res. 54:179-87.

Kaspar, T.C., J.K. Radke, and J.M. Laflen. 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56:160–164.

Keske, C.M.H., D.L. Hoag, A. Brandess, and J.J. Johnson. 2013. Is it economically feasible for farmers to grow their own fuel? A study of Camelina sativa produced in the western United States as an on-farm biofuel. Biomass Bioener. 54:89-99.

Kevin, M.D., D.F. Johnathon, L.W. Donald, M.M. David. 2015. A draft genome of field pennycress (Thlaspi arvense) provides tools for the domestication of a new winter biofuel crop, DNA Res. 22:121–131 https://doi.org/10.1093/dnares/dsu045

Mallarino, A.P., J.E. Sawyer, and S.K. Barnhart. 2013. A general guide for crop nutrient and limestone recommendations in Iowa. PM-1688. Iowa State Univ. Ext. and Outreach, Ames, IA.

Mirsky, S.B., W.S. Curran, D.A. Mortensen, M.R. Ryan, D.L. Shumway. 2009. Control of cereal rye with a roller/crimper as influenced by cover crop phenology. Agron J. 101:1589-1596. doi:10.2134/agronj2009.0130

Noland, R.L., M.S. Wells, C.C. Sheaffer, J.M. Baker, K.L. Martinson, and J.A. Coulter. 2018. Establishment and function of cover crops interseeded into corn. Crop Sci. 58:863-873

Ott, M., C.A. Eberle, D.L. Wyse, F. Forcella, R.W. Gesch. 2015. Improving Minnesota's water quality with cash cover crops. American Society of Agronomy, Crop Science Society of America, Soil Science Society of America Annual Meeting. 18 Nov. 2015, Minneapolis, MN, USA.

Patel, S., J.E. Sawyer, and J.P. Lundvall. 2019. Can management practices enhance corn productivity in a rye cover crop system? Agron. J. 111: 3161-3171.

Patrignani, A., and T.E. Ochsner. 2015. Canopeo: A powerful new tool for measuring fractional green canopy cover. Agron. J. 107:2312-2320.

Putnam, A.R, J. Defrank, and J.P. Barnes. 1983. Exploitation of allelopathy for weed control in annual and perennial cropping systems. J. Chem. Ecol. 9:1001-1010.

Reddy, K., R. Zablotowicz, M. Locke, and C. Koger. 2003. Cover crop, tillage, and herbicide effects on weeds, soil properties, microbial populations, and soybean yield. Weed Science. 51:987-994. doi:10.1614/P2002-169

Royo-Esnal, A., J. Necajeva, J. Torra, J. Recasens, and R.W. Gesch, 2015. Emergence of field pennycress (Thlaspi arvense L.): comparison of two accessions and modelling. Ind. Crop Prod. 66:161-169.

Saini H.S., P.K. Bassi, J.S. Goudey, and M.S. Spencer. 1987. Breakage of seed dormancy of field pennycress (Thlaspi arvense) by growth-regulators, nitrate, and environmental-factors. Weed Sci. 35:802-6.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63:167–179. doi:10.1016/S0167-1987(01)00244-6

Sindelar, A.J., M.R. Schmer, R.W. Gesch, F. Forcella, C.A. Eberle, M.D. Thom, and D.W. Archer. 2017. Winter oilseed production for biofuel in the US Corn Belt: opportunities and limitations. GCB Bioenergy. 9:508-524.

Singer, J.W. 2008. Corn Belt assessment of cover crop management and preferences. Agron. J. 100:1670-1672.

Singer, J.W., S.M. Nusser, and C.J. Alf. 20017. Are cover crops being used in the US corn belt? J. Soil Water Conserv. 62:353-358.

Speddinga, T.A., C. Hamela, G.R. Mehuysa, and C.A. Madramootoob. 2004. Soil microbial dynamics in maize-growing soil under different tillage and residue management systems. Soil Biol. Biochem. 36:499-512.

Soil Survey Staff. Natural Resources Conservation Service, United States Department of Agriculture. Web Soil Survey. https://websoilsurvey.sc.egov.usda.gov/. Accessed May 2017.

Schulz, M., A. Marocco, V. Tabaglio, F.A. Macias, and J.M.G. Molinillo. 2013. Benzoxazinoids in rye allelopathy – From discovery to application in sustainable weed control and organic farming. J. Chem. Ecol. 39:154-174

USDA-NASS. United States Department of Agriculture-National Agricultural Statistics Service. 2016. State agriculture overview. https://www.nass.usda.gov/Statistics_by_State/RFO/index.php. Accessed 2 Feb 2018.

Vaughn SF, Palmquist DE, Duval SM, and Berhow MA (2006) Herbicidal activity of glucosinolate-containing seedmeals. Weed Sci. 54:743–748.

Vetsch, J.A., and G.W. Randall. 2004. Corn production as affected by nitrogen application timing and tillage. Agron J. 96:502-509.

Wilson, M.L., J.M. Baker, and D.L. Allan. 2013. Factors affecting successful establishment of aerially seeded winter rye. Agron. J. 108:1898-1877.

Wright, D., and A.W. Lenssen. 2013. Staging soybean development. Agric. Env. Ext. Pub. 191. http://lib.dr.iastate.edu/extension_ag/pubs/191 (accessed 20 February 2020).

Figures and Tables

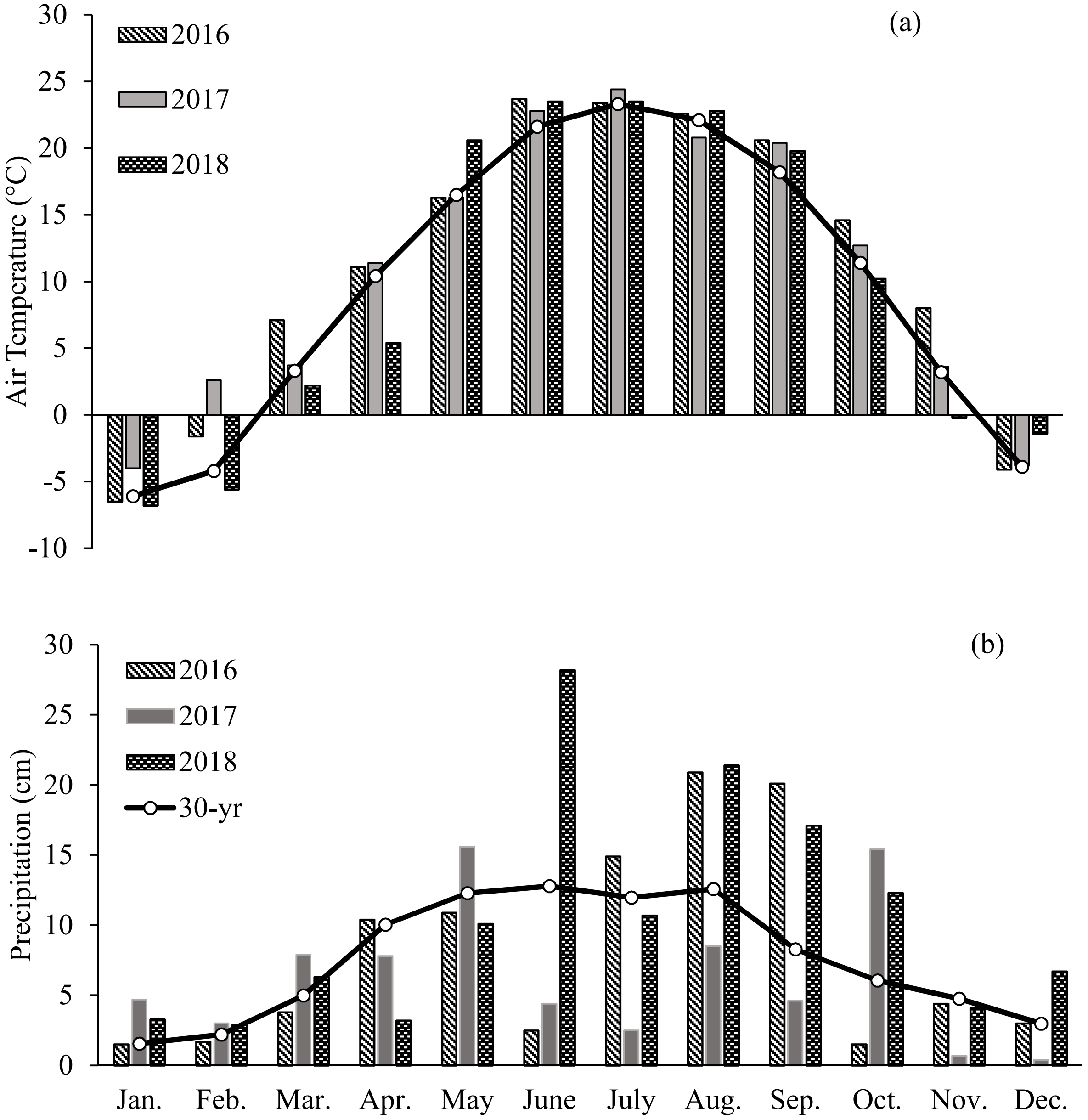

Fig. 1. Monthly mean air temperature (a) and total precipitation (b) for the study years, and the 30-yr mean (1987–2016) (data from Herzmann, 2020).

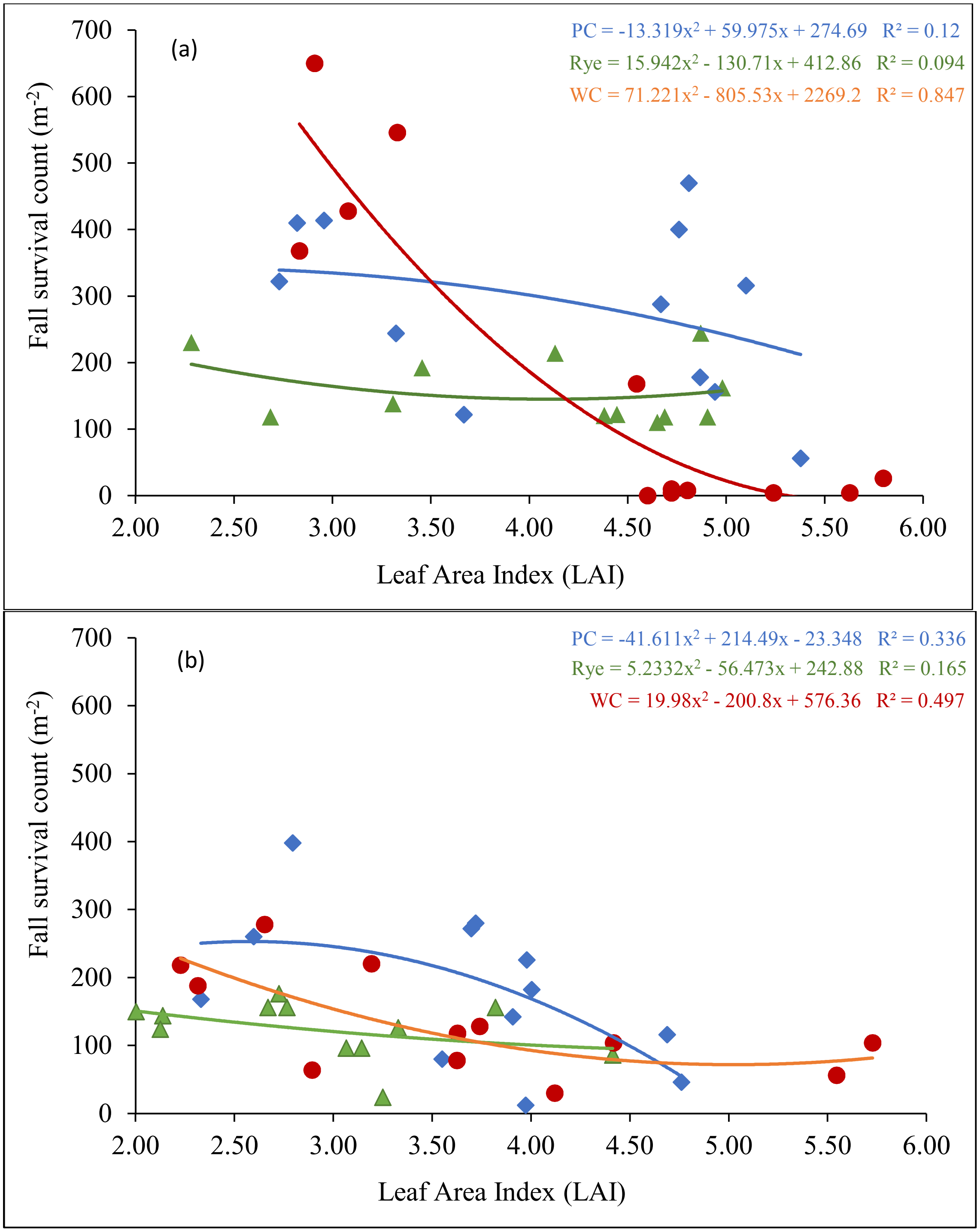

Fig. 2. Cover crop fall stand survival response to corn leaf area index (LAI) at the time cover crop seeding in (a) 2016 and (b) 2017.

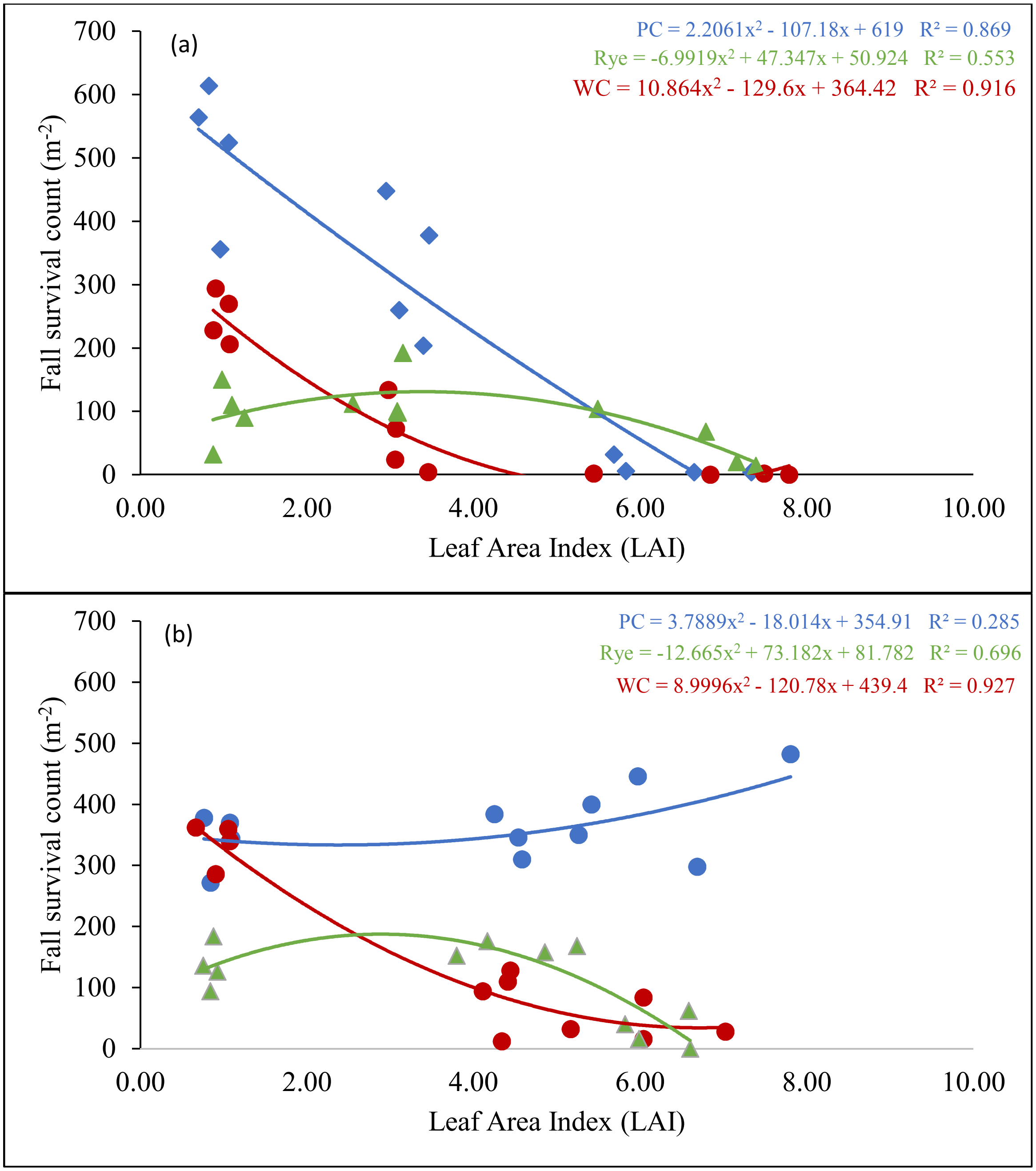

Fig. 3. Cover crop fall stand survival response to soybean leaf area index (LAI) at the time cover crop seeding in (a) 2016 and (b) 2017.

Table 1. Field operations, corn and soybean variety used, seeding and harvest dates, and cover crop seeding dates in corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C) sequence in Ames, IA, in 2016 and 2017.

Tillage	Autumn disk, spring field cultivation
Fertilizer	Corn: 168-123-112 kg ha^{-1} N-P-K Soybean: 48-123-112 N-P_2O_5-K kg ha^{-1}
Herbicides	3.5 L ha^{-1} pendimethalin, 2.2 kg active ingredient ha^{-1} of glyphosate [N-(phosphonomethyl)glycine]
C-S-C	
Corn hybrid	DeKalb DKC57-75RIB
Seeding rate (PLS m^{-2})	8
Seeding date	17 May 2016; 15 May 2017
Harvesting date	13 Oct. 2016; 31 Oct. 2017
S-S-C	
Soybean variety	Asgrow 2663
Seeding rate (PLS m^{-2})[†]	45
Seeding date	17 May 2016; 15 May 2017
Harvesting date	05 Oct. 2016; 18 Oct. 2017
Cover crop inter-seeding date into standing corn	
R4[‡]	09 Aug. 2016; 11 Aug. 2017
R5	01 Sep. 2016; 08 Sep. 2017
R6	29 Sep. 2016; 25 Sep. 2017
Cover crop interseeding date into standing soybean	
R6	18 Aug. 2016; 24 Aug. 2017
R7	12 Sep. 2016; 15 Sep. 2017
R8	30 Sep. 2016; 25 Sep. 2017

[†] PLS = pure live seeds.

[‡] R4, R5 and R6 are interseeding dates for cover crops into standing corn; similarly, R6, R7 and R8 are interseeding dates for cover crops into standing soybean.

Table 2. Treatment means and significance for corn grain yield, protein, oil, and starch at harvest in first year of corn-soybean-corn sequence in 2016 and 2017 at Ames, IA.

	Yield	Protein	Oil	Starch
Treatment[†]	Mg ha^{-1}	---------------------g kg^{-1} ---------------------		
2016				
Control	14.0	77	41	738
PC1	13.2	78	41	736
PC2	12.9	79	42	736
PC3	12.8	78	40	739
Rye1	13.8	79	41	738
Rye2	13.6	78	41	738
Rye3	14.0	77	41	739
WC1	13.5	76	40	739
WC2	14.6	79	42	736
WC3	14.2	74	42	740
SE	0.52[‡]	1.65	0.96	2.39
P > F				
Control vs. PC	NS[‡]	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS
2017				
Control	12.0	67	33	703
PC1	13.1	67	35	703
PC2	12.1	66	34	705
PC3	12.5	67	35	702
Rye1	11.9	67	33	704
Rye2	11.7	69	35	701
Rye3	11.3	67	34	704
WC1	13.2	70	35	700
WC2	11.7	68	34	703
WC3	12.1	68	33	703
SE	0.66	1.70	1.03	2.42
P > F				
Control vs. PC	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

[†] Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

[‡] Indicates weighted SE for all variables.

Corn and soybean yields are expressed at 155 and 130 g kg^{-1} moisture, respectively.

Table 3. Treatment means and significance for soybean seed yield, protein, oil, and fiber at harvest in first year of soybean-soybean-corn sequence in 2016 and 2017 at Ames, IA.

	Yield	Protein	Oil	Fiber
Treatment[†]	Mg ha^{-1}	---------------------g kg^{-1}		---------------------
		2016		
Control	4.1	341	187	49
PC1	4.0	342	186	48
PC2	4.0	342	185	49
PC3	4.3	343	185	48
Rye1	4.1	341	185	49
Rye2	3.8	341	185	49
Rye3	4.0	339	187	48
WC1	4.2	343	185	48
WC2	3.9	346	184	48
WC3	4.1	346	184	48
SE	0.22[‡]	2.04	1.28	0.24
		$P > F$		
Control vs. PC	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS
		2017		
Control	3.5	328	173	43
PC1	3.8	331	174	42
PC2	3.4	331	173	42
PC3	3.4	327	176	43
Rye1	3.5	328	173	43
Rye2	3.4	324	176	43
Rye3	3.5	323	178	42
WC1	3.5	327	174	42
WC2	3.3	326	176	43
WC3	3.8	328	176	42
SE	0.13	1.72	0.95	0.21
		$P > F$		
Control vs. PC	NS	NS	NS	*
Control vs. Rye	NS	NS	*	NS
Control vs. WC	NS	NS	NS	*
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	**	*
Cover × SD	*	NS	NS	*

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

[†] Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

[‡] Indicates weighted SE for all variables.

Corn and soybean yields are expressed at 155 and 130 g kg^{-1} moisture, respectively.

Table 4. Treatment means and significance for soil moisture (0-30 and 30-6- cm) in fall after corn harvest and in spring at rye termination in corn-soybean-corn sequence initiated in 2016 and 2017 at Ames, IA.

	Soil moisture			
	Fall		Spring	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Treatment[†]	-------------------------g kg^{-1}------------------------			
	2016			
Control	174	176	181	192
PC1	184	185	179	182
PC2	170	186	176	195
PC3	176	190	180	192
Rye1	176	185	168	180
Rye2	192	191	170	195
Rye3	179	186	177	180
WC1	169	170	173	177
WC2	198	189	189	182
WC3	182	178	175	192
SE	8.1[‡]	11.2	8.0	12.7
	P > F			
Control vs. PC	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS
	2017			
Control	200	212	230	246
PC1	192	218	212	231
PC2	186	195	197	212
PC3	197	201	206	242
Rye1	209	228	216	253
Rye2	180	194	222	222
Rye3	190	197	203	233
WC1	222	228	217	249
WC2	198	193	207	211
WC3	190	206	191	234
SE	20.2	20.8	15.8	19.9
	P > F			
Control vs. PC	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS

[†] Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

[‡] Indicates weighted SE for all variables.

Table 5. Treatment means and significance for soil moisture (0-30 and 30-6- cm) in fall after soybean harvest and in spring at rye termination in soybean-soybean-corn sequence initiated in 2016 and 2017 at Ames, IA.

	Soil moisture			
	Fall		Spring	
	0-30 cm	30-60 cm	0-30 cm	30-60 cm
Treatment[†]	------------------------ g kg^{-1}------------------------			
	2016			
Control	178	176	185	188
PC1	170	181	187	194
PC2	174	182	184	190
PC3	180	185	189	195
Rye1	178	182	194	196
Rye2	170	168	186	177
Rye3	172	183	186	197
WC1	173	183	183	190
WC2	175	184	184	195
WC3	179	181	185	199
SE	4.8[‡]	7.4	6.3	9.0
	P > F			
Control vs. PC	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS
	2017			
Control	190	209	208	220
PC1	171	198	233	222
PC2	192	212	213	229
PC3	190	208	203	226
Rye1	179	203	226	224
Rye2	199	219	208	243
Rye3	193	199	204	225
WC1	205	198	202	238
WC2	202	200	242	215
WC3	185	213	203	239
SE	16.7	19.1	19.2	20.2
	P > F			
Control vs. PC	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS

[†] Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

[‡] Indicates weighted SE for all variables.

Table 6. Treatment and significance for cover crop survival index (SI) and stand density, aboveground biomass (DM), and green cover (GC) in fall after corn harvest and in spring at rye termination in 2016 and 2017 at Ames, IA.

	SI	Stand density		DM		GC	
Treatment[†]		Fall	Spring	Fall	Spring	Fall	Spring
		------m^{-2}------		------Kg ha^{-1}------		---------%---------	
			2016				
PC1	2.77a§	128dc	27	75cb	303	8.8de	17.2
PC2	0.72cde	369b	196	92b	1228	18.7bcd	38.4
PC3	0.79bcde	348b	229	55bcd	820	8.7ed	32.3
Rye1	1.28bc	118dc	57	284a	3440	24.4ab	54.0
Rye2	1.15bcd	185c	87	311a	3870	32.5a	64.1
Rye3	1.79ab	170c	134	123b	2620	21.1bc	51.6
WC1	1.02bcde	6e	1	2d	0.0	0.8e	10.5
WC2	0.16de	52de	7	7cd	80	1.7e	7.3
WC3	1.57bc	498a	151	56bcd	565	13.7cd	23.7
SE	0.3[‡]	34	33	25	430	3.5	6.6
			P > F				
Rye vs. PC	NS	***	*	***	***	***	***
Rye vs. WC	NS	NS	NS	***	***	***	***
PC vs. WC	NS	**	**	*	NS	*	**
SD1 vs. SD2	**	***	*	NS	NS	*	NS
SD1 vs. SD3	NS	***	***	****	NS	NS	NS
SD2 vs. SD3	*	***	**	**	NS	NS	NS
Cover × SD	**	***	NS	***	NS	*	NS
			2017				
PC1	0.17b	64fe	26cd	19	97	3.3	13.2
PC2	3.35a	206bc	169a	37	214	3.5	9.0
PC3	0.42b	277a	117ab	26	107	2.4	7.5
Rye1	1.29b	106de	46cd	206	1274	8.8	51.9
Rye2	0.76b	139dc	81bc	90	1504	8.2	59.7
Rye3	0.78b	129de	130ab	134	1175	7.2	52.7
WC1	0.25b	77de	27cd	21	89	1.2	2.3
WC2	0.22b	94de	44cd	14	96	0.4	4.8
WC3	0.45b	226ab	51cd	26	126	0.8	4.8
SE	0.5	24	21	22	137	1.3	5.2
			P > F				
Rye vs. PC	NS	**	NS	***	***	***	***
Rye vs. WC	NS	NS	*	***	***	***	***
PC vs. WC	*	*	***	NS	NS	*	NS
SD1 vs. SD2	NS	**	***	NS	NS	NS	NS
SD1 vs. SD3	NS	***	***	NS	NS	NS	NS
SD2 vs. SD3	NS	**	NS	NS	NS	NS	NS
Cover × SD	**	**	*	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

[†] Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

[‡] Indicates weighted SE for all variables.

§Means followed by a same letter in a column within the year are not statistically significant at P=0.05.

Table 7. Treatment and significance for cover crop survival index (SI) and stand density, aboveground biomass (DM), and green cover (GC) in fall after soybean harvest and in spring at rye termination in 2016 and 2017 at Ames, IA.

	SI	Stand density		DM		GC	
Treatment[†]		Fall	Spring	Fall	Spring	Fall	Spring
		------m^{-2}------		------Kg ha^{-1}------		---------%---------	
			2016				
PC1	0.03	12d§	45	12	413	1.9	12.6
PC2	0.65	323b	178	154	1129	15.2	31.6
PC3	0.77	515a	238	36	1010	8.8	37.1
Rye1	0.38	52cd	63	200	1780	16.0	46.0
Rye2	0.63	134c	110	381	1717	31.5	45.7
Rye3	0.59	96c	101	157	1834	15.9	43.8
WC1	0.09	3d	0	0.2	0.0	0.8	2.3
WC2	0.86	54cd	100	66	591	5.5	17.0
WC3	0.25	250b	104	30	601	5.2	24.3
SE	0.2[‡]	30	39	51	385	3.2	7.6
			$P > F$				
Rye vs. PC	NS	***	NS	***	**	***	**
Rye vs. WC	NS	NS	NS	***	***	***	***
PC vs. WC	NS	***	*	NS	NS	NS	*
SD1 vs. SD2	***	***	**	**	NS	**	NS
SD1 vs. SD3	**	***	**	NS	NS	NS	*
SD2 vs. SD3	NS	***	NS	**	NS	**	NS
Cover × SD	NS	***	NS	NS	NS	NS	NS
			2017				
PC1	1.08	407a	157a	52c	352bcd	0.20	21.0bc
PC2	1.77	435a	115b	50c	433bc	0.45	25.5b
PC3	1.24	341a	133ab	9d	258bcd	0.43	17.6bcd
Rye1	1.55	30c	12de	13d	317bcd	0.34	21.4b
Rye2	1.30	164b	71c	164a	1537a	0.56	70.9a
Rye3	0.99	135b	122ab	78b	1271a	0.13	59.4a
WC1	0.86	35c	3de	0.4d	17cd	0.43	3.0de
WC2	0.46	91bc	41cd	17d	145bcd	0.04	6.3cde
WC3	0.62	337a	143ab	16d	444b	0.64	20.7bc
SE	0.3	34	15	7	1	0.3	5.8
				$P > F$			
Rye vs. PC	NS	***	***	***	***	NS	***
Rye vs. WC	*	NS	NS	***	***	NS	***
PC vs. WC	**	***	***	***	NS	NS	*
SD1 vs. SD2	NS	*	NS	***	***	NS	***
SD1 vs. SD3	NS	***	***	*	**	NS	***
SD2 vs. SD3	NS	NS	***	***	NS	NS	NS
Cover × SD	NS	***	***	***	**	NS	***

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

[†] Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

[‡] Indicates weighted SE for all variables.

§Means followed by a same letter in a column within the year are not statistically significant at P=0.05.

Table 8. Treatment means and significance for weed density in spring at rye termination in corn-soybean-corn and soybean-soybean-corn sequence initiated in 2016 and 2017 at Ames, IA.

	C-S-C		S-S-C	
	2016	2017	2016	2017
Treatment†	--------------------plants m^{-2}--------------------			
Control	92	26	110	45
PC1	21	17	55	19
PC2	20	14	25	19
PC3	13	18	21	32
Rye1	7	11	8	25
Rye2	12	11	21	20
Rye3	6	10	14	52
WC1	60	28	137	45
WC2	74	21	111	32
WC3	17	17	63	28
SE	26.9	4.0	26.7	12.7
	$P > F$			
Control vs. PC	*	*	*	NS
Control vs. Rye	*	**	**	NS
Control vs. WC	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS
Control vs. SD2	NS	*	NS	NS
Control vs. SD3	*	*	**	NS
Cover × SD	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

†Control treatment with no cover crop. PC1-PC3 are pennycress cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), Rye1-Rye3 are rye cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean), and WC1-WC3 are camelina cover crop seeded at R4, R5 and R6 (corn) and R6, R7 and R8 (soybean).

‡Indicates weighted SE for all variables.

CHAPTER 3. INTERSEEDED PENNYCRESS AND CAMELINA YIELD AND THEIR INFLUENCE ON ROW CROPS

Swetabh Patel*, Andrew W. Lenssen, Kenneth J. Moore, Yesuf A. Mohammed, Russ W. Gesch, M. Scott Wells, Burton L. Johnson, Marisol T. Berti, and Heather L. Matthees

S. Patel, A.W. Lenssen, K.J. Moore, Dept. of Agronomy, Iowa State Univ., Agronomy Hall, Ames, IA 50011-1010, USA; R.W. Gesch, Y.A. Mohammed, USDA-ARS North Central Soil Conservation Research Lab, Morris, MN 56267 USA; M.S. Wells, Dept. of Agronomy and Genetics, Univ. of Minnesota., Borlaug Hall, St. Paul, MN 55108, USA; B.T. Johnson, M.T. Berti, Dept. Plant Sciences, North Dakota State Univ., Loftsgaard Hall, Fargo, ND 58102, USA; H.L. Matthees, WinField United, Land O'Lakes, Arden Hills, MN 55112.

Modified from a manuscript under review in Agronomy Journal

Abstract

Field pennycress (*Thlaspi arvense* L.) (PC) and winter camelina [*Camelina sativa* (L.) Crantz] (WC) have potential to provide ecosystem services and economic incentives when adopted as crops in corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.] rotations. However, establishment and seed yield of these oilseed cover crops in the northern Corn Belt and their subsequent impact on row crops is not well known. The objectives of these study were to determine the effects of interseeding dates and oilseed cover crop species on seed and oil content (PC and WC), relay soybean yield, and third year corn grain yield and grain qualities. The interseeding dates were R4, R5, and R6 development sages for corn and R6, R7 and R8 development stages for soybean. The cover crop species were PC, WC, winter rye and control (no cover crop). Study sites were initiated near Ames, IA; Morris and Rosemount, MN; and Prosper, ND. Late interseeding of PC and WC resulted in greater PC and WC oilseed yield than early interseeding. However, overall seed yields of PC (218–880 kg ha^{-1}) and WC (15-770 kg ha^{-}

^{1}) averaged across interseeding dates were low in both corn and soybean. The PC and WC reduced relayed-soybean grain yield compared to control by 13 to 32% and 12 to 22%, respectively. Corn grain yield and quality following relay soybean were not affected by residual effects of oilseed crops. Further research is needed to identify the best management practices to integrate PC and WC into corn-soybean rotations in upper Midwest.

Key words: camelina; corn; pennycress; relay cropping; soybean

Abbreviations: NPG, northern Great Plains; PC, field pennycress; WC, winter camelina.

Introduction

Corn soybean and their rotation with winter fallow forms the predominant cropping system in the upper Midwestern United States (Minnesota, Wisconsin, Michigan, Illinois, Iowa, South Dakota, and North Dakota). This cropping system is high yielding and economically successful, but the long-term productivity and sustainability of such systems is questionable (Power and Follett, 1987; Reganold et al., 1990; Crookston et al., 1991; Jones and Singh, 2000). The typical cropping system in the upper Midwest has an absence of living ground cover following corn and soybean harvest that frequently leads to soil erosion (Laloy and Bielders, 2010) and excessive loss of nutrients (Patel et al., 2019) due to lack of synchronization between nutrient availability and plant uptake (Myers, 1994). Concern over the excess use of nitrogen in the system, its losses during production and non-crop fallow, and subsequent impacts on environmental quality argue for the development of more sustainable cropping practices. Integration of cover crops in the existing cropping system is considered an effective strategy for improving sustainable production. Usually seeded in fall before row crop maturity or shortly after harvest, cover crops offer protection to the soil from wind and water erosion by providing surface cover. Despite several proven benefits of cover crops (Dabney et al., 2001; Kaspar et al., 2001; Sainju et al., 2002; Blanco-Canqui et al., 2017), the rate of cover crop adoption by farmers is still low (Kladivko et al., 2014) due to issues related to cover crop management and lack of immediate economic incentive (Plastina et al., 2018).

The use of cover crops, common in the eastern and central Corn Belt, are uncommon in corn-soybean systems in the northern Great Plains (NGP) due to the short growing season and unpredictable weather conditions within and among growing seasons. Lack of winter soil cover increases soil organic matter and nutrient losses, resulting in decreased crop productivity and resiliency (Berti et al., 2017a). Innovative cropping systems are necessary to achieve continuous and sustainable supplies of food, feed, fuel, and bio-based products. Double- (Hexen and Boxley, 1986) and relay cropping (Kline et al., 2003) systems are an option to produce biofuels, food, and biomass feedstock in a single season on the same land without sacrificing food security (Berti et al., 2015). Winter camelina (WC) and field pennycress (PC) are oilseed crops gaining attention due to their capacity to provide industrial feedstock for biofuels, lubricants, and plastics as well as to enhance agro-ecosystem services (Berti et al., 2016; Cubins et al., 2019). Integrating these crops as winter annuals between main summer crops can provide additional economic benefits (Gesch et al., 2014). Due to limited time to establish these crops after corn and soybean harvest and before winter freeze, interseeding into standing maize and soybean could be an option and would improve land use efficiency in corn-soybean cropping systems by temporal intensification through the inclusion of WC and field PC as cover crops and/or oilseed crops (Royo-Esnal et al., 2015; Berti et al., 2017b; Peterson et al., 2019). Interseeding of winter annuals into corn and soybean is possible in the NPG and Upper Midwest (Berti et al., 2017b; Johnson et al., 2017; Noland et al., 2018;). However, better seeding practices and agronomic management is required to improve yields of oilseed cover crops when used in corn-soybean system (Gesch and Cermak, 2011; Noland et al., 2018; Mohammed et al., 2020) and additional environmental (Eberle et al., 2015; Johnson et al., 2017) and rotational benefits of these cover crops require better documentation to increase their adoption by growers.

Successful integration and subsequent adoption of these oilseed cover crops into existing corn-soybean systems in the northern Corn Belt is in part contingent upon the information regarding effect on row crop yields in double- or relay cropping system. The objectives of this study were to: i) quantify the field PC and WC oilseed yields when planted at late-season dates in standing corn and soybean; ii) determine the effect of oilseed cover crops on relay-planted soybean yield; and iii) investigate for residual effects of oilseed cover crops on yield and quality of corn planted in the year following relay soybean harvest.

Materials and Methods

Site Description

A field study investigating two three-year crop sequences was initiated in the spring of 2016 near Ames, IA; Prosper, ND; Morris, MN; and Waseca, MN. The three-year sequences were replicated in time the following year, 2017, by starting each sequence again near Ames, Prosper, and Morris. However, in 2017 Rosemount, MN was used to replace Waseca due to severe flooding in 2016. The soil types at each respective site were: Ames, IA (42° 00' N, - 93°44' W) with Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll) and Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll); Morris, MN (45°40′ N, -95°48′ W) with Hokans (fine-loamy, mixed, superactive, frigid Calcic Hapludolls)-Svea (fine-loamy, mixed, superactive, frigid Pachic Hapludolls) complex; Rosemount, MN (44°42′ N, -93°03′ W) with Waukegon silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls); and Prosper, ND (46°58′ N, -97°03′ W) with Bearden silt loam (fine-silty, mixed, superactive, frigid Aeric Calciaquolls). Weather data including monthly mean temperature and rainfall across all years and locations were collected using a weather station near each site.

Plot Design and Treatment Implementation

The experiments were established in two separate three-year rotation systems, corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C). The experimental design at Ames, Morris, and Rosemount was a randomized complete block in a split-plot arrangement with four replicates. The main plot (9.1 m x 7.6 m) consisted of three different seeding dates: R4, R5, and R6 developmental stage in corn as per Abendroth et al. (2011); R6, R7, and R8 developmental stage in soybean as per Wright and Lenssen (2013) while the subplot (3.0 m x 7.6 m) consisted of three cover crops, PC, WC, and cereal rye (*Secale cereale* L.). A control plot with no cover crop was present in each replicate to represent a conventional corn and soybean cropping system. At all sites, corn, and soybean cultivars or hybrids well adapted to the respective area were seeded in 76-cm row spacing using a four or six-row planter depending on site. At Prosper, the experimental design was a RCBD with factorial arrangement of the same seeding dates and cover crops mentioned above, and a control (no cover crop) treatment with four replicates.

Cover Crop Seeding and Harvest

Recommended crop management practices specific to each location were used for corn and soybean management. At all sites, 1064, 1368, and 222 pure live seeds (PLS) m^{-2} of field PC (cv. MN106), WC (cv. Joelle), and winter rye (cv. Rymin), respectively, were broadcast seeded in standing corn or soybean at different reproductive stages during the first year of the rotation. At Ames and Prosper, PC, WC, and rye were hand-broadcast followed by light raking, whereas at Morris and Rosemount, a modified high-clearance tractor, Lee Avenger (LeeAgra, Inc., Lubbock, TX), was used to broadcast cover crop seeds with shallow incorporation. Cover crop seeding and harvest date varied among sites (Table 1) due to differences in growth stage of corn or soybean and varying maturity dates of cover crops. Rye was terminated in spring before planting soybean whereas, PC and WC was harvested for oilseed later in summer at their respective maturity. At the harvest of PC and WC, total number of plants were counted, and then aboveground biomass was harvested from 0.76 m^2 from the center-two rows of each plot. Seeds from PC and WC silicles were separated and cleaned with combinations of sieves and air column separater and then weighed to determine seed yield ha^{-1}. Winter camelina and PC seed oil content was measured by pulsed nuclear magnetic resonance (Bruker Minisepc mq10, Bruker, The Woodlands, TX). This instrument was calibrated with known quantities of pure oil for both species. In brief, seeds of WC and PC were dried at 130 ^{o}C for 4 h and cooled in a desiccator for 15 min before measuring oil content. Then, approximately 5 g of this seed sample was used for oil content testing. For PC and WC seed carbon and nitrogen content determination, the seeds were dried at 65 ^{o}C until constant dry mass was achieved and ground to pass through a 0.425 mm screen. Then, oilseeds carbon and nitrogen content were determined using 0.2 g of this ground sample following dry combustion with Leco CN828 (LECO Corporation, St. Joseph, MI, USA). PC and WC seeds from Prosper in 2017 and 2018 for C-S-C system could not be analyzed for seed quality due to insufficient sample size.

Relay Soybean Seeding and Harvest

In the spring of the second year of both C-S-C and S-S-C sequences, soybean was relay-planted (Table 1) into PC and WC along with terminated rye plots and no cover control plots when soil temperature was predicted to remain above 10^{o}C. Rye was terminated using glyphosate [N-(phosphonomethyl)glycine] in spring at least 2 to3 days before seeding soybean. PC was flowering while WC was at bolting stage when soybean was relay planted after rye termination. Standard weed management practices using herbicide applications were used for soybean production at each site.

Soybean yield components (plant height, node number, and silicle count) were measured from six individual plants in the center of each row before harvesting the relay soybean. Grain yield of soybean was determined by harvesting the center-two rows of each plot with a self-propelled combine. At Rosemount and Prosper, soybean yield component data were not collected from either crop sequence in 2018. Soybean seeds were analyzed for oil, C and N concentration using similar methods as mentioned above for PC and WC.

Year Three Corn Seeding and Harvest

At all sites in the year following relay soybean harvest, corn was no-till planted in the spring in both the C-S-C and S-S-C sequences. Corn hybrids suited for each location was used and locally recommended fertilizer (types and rates) and weed management practices applied. Corn grain yield was calculated following combine harvest of the center-two rows from each plot and reported at 155 g kg^{-1} moisture. Corn seed samples from each plot were collected at harvest and analyzed for seed N and C concentration using similar method as described above for PC and WC. Seed quality results are presented from all the sites, except for 2018 from Rosemount.

Soil Sampling and Moisture Determination

Soil samples from 0-30 cm and 30-60 cm depths were collected from all the treatments at the time of PC and WC harvest using a hand pushed probe (JMC Soil Samplers, Newton, IA, USA). Three random cores of soil samples were collected and composited from the center-two rows of each plot using a 1.7-cm diameter soil probe. Soil samples were weighed at field moist condition and then were dried at 105□ for 48 h until reaching a constant weight and then weighed again to determine dry weight. The percent soil moisture concentration was calculated on a dry soil weight basis and presented in g kg^{-1}. Soil samples were not collected at cover crop harvest from Prosper in 2017 or 2018.

Statistical Analysis

Data from the two cropping sequences (C-S-C and S-S-C) were analyzed separately using SAS 9.4 (SAS Institute. 2014). For each system, a combined analysis of variance was performed across all locations (Ames, Morris, and Rosemount) using a mixed linear model as suggested by Moore and Dixon (2015). Environment (year × location), replicate, and their interaction with seeding date and cover crop species were considered random while seeding date, cover crop entry, and their interaction were considered as fixed effects in the linear model. Due to incomplete factorial design of the experiments, contrast statements were used for comparing treatments and individual mean comparisons were made using the LSD at P=0.05. Data from the C-S-C sequence at Rosemount were not included in the combined analysis due to smothering of cover crops in the absence of proper corn residue management as described in the related study by Mohammed et al. (2020). Data from Prosper site were analyzed for a randomized complete block using a mixed model and presented separately due to use of a different experimental design.

Results and Discussion

Weather Conditions

Weather conditions such as soil temperature and snow cover during winter can influence the overwintering capacity and survival of established cover crops. Winter temperatures (Jan. Feb) in 2017 were 5°C and 3°C above the long term mean across the sites and at Prosper, respectively. However, in 2018 and 2019, monthly air temperatures from Dec. to Feb. in Iowa and Minnesota sites were 1 and 3°C lower, respectively (Table 2). At Prosper, month of Jan-Feb. was 3 and 5°C below the 30-yr mean in 2018 and 2019, respectively. Total rainfall in 2017 winter (Jan. and Feb.) was 1-cm greater whereas in 2019 was about 2-cm above the 30-yr average (Table 2).

Weather conditions during cover crop growth in the spring are important and influence growth and biomass accumulation and can subsequently affect flowering and seed yield of oilseed cover crops. Spring weather conditions also are important for timely seeding of row crops and their subsequent emergence and early season growth. Spring (March-May) temperatures in 2017 and 2018 was similar but 2019 across locations was 2°C colder across the sites. Prosper was 2-3°C below average in 2018 and 2019 spring. Spring in 2018 was drier across all the locations including Prosper, whereas, total spring rainfall in 2017 and 2019 was higher than the long-term mean with May in 2017 and 2019 receiving 4- and 6-cm more rainfall than the 30-yr average, respectively at Iowa and Minnesota locations. Similarly, in 2018, June received more than 6 cm of rain than the long-term average.

Summer is the period of active growth of row crops and weather conditions during this play a crucial role in biomass accumulation and reproduction. Summer (June-Aug.) in 2017 and 2019 across all three sites was slightly warmer than the average, whereas, at Prosper, summer temperatures were similar to the long-term mean throughout the experimental years. In Iowa and Minnesota, summer in 2017 was dry, wet in 2018 and slightly received slightly below normal rainfall in 2019. An excess of rainfall up to 2-6 cm compared with long-term normal was observed in the month of June and August in 2018. At Prosper, 2017 summer was dry while 2019 received an excess of 13cm rainfall in summer.

Average temperature in the fall (Sept-Nov) of 2018 and 2019 was 2- to 4-°C lower with temperatures in the fall of 2018 being similar to long-term average. Fall temperatures at Prosper was 3 below and above in 2018 and 2019, respectively. Fall of 2018 and 2019 were considerably wet and received an excess rainfall of 8- and 6-cm above the 30-yr average, respectively.

Rainfall in excess of 3 and 10cm was also received in at Prosper in the experimental year 2017 and 2019.

Pennycress and Camelina Seed Yield and Quality

Cover crop survival after the winter and its subsequent growth and biomass accumulation in spring can be affected by seeding date into standing row crops (Mohammed et. al., 2020). Moreover, time of cover crop seeding in fall can influence germination and establishment under the row crop canopy. In this experiment, poor establishment of PC and WC in the fall and low survival during winter (Mohammed et. al., 2020) resulted in overall low oilseed yield for PC and WC in both C-S-C and S-S-C sequences (Table 3 and 4). Across all locations, mean seed yield of PC across seeding dates was significantly greater than WC in both sequences (Table 3). The higher yield of PC likely resulted from better fall establishment and winter survival (Mohammed et al., 2020). Mean yield of PC and WC was 344 and 201 kg ha^{-1} for C-S-C and 763 and 318 kg ha^{-1} for S-S-C rotation systems, respectively. Oilseed yield in our study were much lower compared with PC and WC yields of 1550 and 1100 kg ha^{-1}, respectively, reported by Ott et al. (2019) in Minnesota where PC and WC was planted in early autumn (late Aug.-Sept.) into winter wheat stuble. Soybean should ideally be relay planted into the PC and WC before their bolting stage (Gesch et al. 2014), but due to prolonged cold soil temperatures, soybean seeding was often delayed during this study resulting in delayed wheel traffic which may have reduced seed yield of oilseed cover crops.

Across both the oilseed cover crops (PC and WC), later seeding dates in corn (R6) and soybean (R8) resulted in greater yield of PC and WC, thus indicating that later seeding in the fall into standing corn and soybean is advantageous for seed yield. Higher seed yields of PC (Bishop and Nelson, 2018) and WC (Gesch and Cermak, 2011; Berti et al., 20217b) with late seeding in the fall was previously reported. Prolonged time with inadequate light penetration under the corn and soybean canopy with early seeding dates could prevent PC and WC survival when seeded at earlier reproductive stages of corn and soybean (Mohammed et al., 2020).

At Prosper, PC and WC oilseed yields were not significantly different in the C-S-C sequence and averaged 259 and 68 kg ha^{-1}, respectively (Table 4). In the S-S-C sequence, PC yield was 47% greater compared with that of WC. Conversely, seed oil, N, and C concentrations were 17, 13, and 5% greater in WC than PC seeds, respectively. Seeding date of oilseed cover crops did not influence seed yield, seed oil and N concentration. However, seed C concentration was slightly higher when seeded early (R7) in soybean compared with late seeding (R8).

Oil concentration of WC and PC across site years was not affected by either seeding date or its interaction with cover crop species in C-S-C sequence (Table 3). However, in S-S-C sequence, oil concentration was higher with later seeding dates (R7 and R8) as compared with earlier date (R6). Despite the low seed yield compared with PC, oil concentration of WC was 3.5% higher in both sequences (Table 3). Averaged across all seeding dates, seed oil concentration for PC was 281 and 292 g kg^{-1} and for WC was 315 and 324 g kg^{-1} in corn and soybean systems, respectively. Similar range of oil concentrations for PC were reported by Dose et al. (2017) and Gesch and Cermak (2011), respectively. However, the oil concentration for WC were much lower than what have been reported in previous studies (Gesch et al. 2014; Gesch et al. 2018) which seems to indicate that plants were stressed and thus resulted in unusually low oil contents.

Seed N concentration followed a similar trend as oil and was higher in WC compared with PC (Table 3). Interseeding date and its interaction with cover crop species did not influence oilseed N concentration. However, WC had higher N compared with PC in both sequences. The

N concentration of WC seeds was similar (44 g kg^{-1}) in both the systems whereas PC had 42 and 41 g kg^{-1} N in corn and soybean system, respectively.

Oilseed C concentration was not affected by cover crop species in either C-S-C or S-S-C system and averaged around 540 g kg^{-1} for both the oilseed cover crops (Table 3). Similarly, interseeding date did not affect C concentration in corn system and averaged 545 g kg^{-1} across all seeding dates. However, in soybean system, oilseed carbon concentration was slightly higher with R8 seeding date (554 g kg^{-1}) whereas it did not significantly differ between R6 (529 g kg^{-1}) and R7 (536 g kg^{-1}) seeding date.

Soil Moisture at Oilseed Harvest

Moisture in the upper surface soil at the time of soybean seeding is highly important for germination and initial soybean growth since the root system is not yet fully developed. Therefore, insufficient soil moisture during the initial growth phases can negatively affect the soybean growth and development. An actively growing cover crop in the spring can transpire a significant amount of moisture from soil which can result in adequate soil moisture for germination of a relay-planted or conventionally planted row crop in years with inadequate rainfall for recharging soil moisture. Soil moisture can be critical for the row crop later in the summer when there are less chances of receiving rainfall. Previous studies have shown that cover crops can play important roles in reducing and conserving soil moisture at different times of the year (Munawar et al., 1990; Raimbault et al., 1991; Wells at al., 2014) and thus affect growth and seed yield of row crops (Basche et al., 2016). Results of our study indicate that in both C-S-C and S-S-C sequences, soil profile moisture at 0-30 cm and 30-60 cm at cover crop harvest was not influenced by either the type of cover crop or the fall seeding date of cover crops (Table 5). Mean soil moisture across all the treatments in the top 30-cm and 30-60 cm were similar and averaged about 20 g water kg^{-1} soil. Lack of differences in soil moisture in the topsoil profile are explained by wet springs in 2017 and 2018 (Table 2). These results indicate that in years with wet spring, PC, WC, and rye (Appelgate et al., 2017) as cover crops will have access to sufficient soil moisture and thus avoid any negative effects on moisture availability of a relayed crop.

Relay Soybean, Plant Height, Number of Nodes and Silicles Per Plant, Seed Yield and Nutrient Composition

Plant height, number of nodes, and silicles can be indicators of seed yield (Board, 1985). Some of the yield components may be affected by relay seeding and later may be reflected in the soybean seed yield (Wallace et al. 1996). In our study, soybean seed yield components evaluated were not influenced by either crop species or their seeding date in the C-S-C sequence (Table 5). In the S-S-C sequence, mean soybean plant height at harvest was similar for the rye and no cover crop treatments, but plant height was reduced by 9- and 7-cm when soybean was relay planted into standing PC and WC, respectively (Table 5). Late-seeded WC and PC (R7 and R8) reduced the relay soybean plant height at harvest as compared with the control treatment. Although, WC reduced the total number of nodes on the main stem by 5%, the mean number of silicles plant^{-1} was not affected by either cover crop treatment or seeding date in S-S-C system. At Prosper, similar trends were seen in both C-S-C and S-S-C systems and number of nodes plant^{-1} and plant height were reduced by the PC and WC from all three seeding dates (Table 6). Similar to the other locations, rye did not affect either the number of nodes plant^{-1} or the soybean plant height. The total number of silicles plant^{-1} were not affected by cover crop species, seeding date or their interaction in both the rotation systems at the Prosper site.

In a relay cropping system, moisture and nutrient availability could become a limiting factor when soybean is planted into cover crops (Duncan and Schapaugh, 1997) and can affect the yield of both the crops resulting in decreased yield as compared with a single crop. At Ames, Morris, and Rosemount, relay soybean yield in the S-S-C sequence was not affected by cover crop species and seeding date or their interaction. However, in the C-S-C sequence, both PC and WC reduced relay-planted soybean seed yield by 15.6 and 12.5 %, respectively (Table 5). However, the herbicide terminated rye cover crop did not affect the relay soybean seed yield in either sequence.

At Prosper, relay soybean seed yield was reduced by PC in both three-year sequences whereas WC decreased soybean yield only in the S-S-C system. The rye cover crop, however, did not affect yield of soybean when compared with the no cover crop control. Field pennycress reduced soybean yield by 32 and 28% in C-S-C and S-S-C sequences, respectively, whereas WC reduced relay soybean yield by 41% in S-S-C system. Reduction in relay soybean yield in our study is greater or in some cases similar to previous studies (Johnson et al. 2017; Ott et al. 2019). Johnson et al. (2017) saw reductions in soybean yields of about 20 to 30% when relayed with either PC or WC and Gesch et al. (2014) reported yield reductions of 25 to 33%.

The overall productivity of a relay cropping system can be increased when the yields of both crops are combined for the system (Gesch et al., 2014; Johnson et al. 2017; Ott et al., 2019). However, in our study, the total yield (soybean and oilseed cover crop) of relay system across site-year was reduced in the C-S-C system (Fig. 1). Total relay system yield compared with monocrop soybean was reduced by 2% and 7% with PC and WC, respectively in the C-S-C sequence. However, total oilseed yield of the relay system was increased by 21% with PC and was similar with WC in the S-S-C sequence across all site years. At Prosper, relay interseeding soybean in both PC and WC reduced the total oilseed yield in both three-year sequences (Fig. 2). Total oilseed yield of the relay system with interseeding soybean into PC and WC was 75% and 80% and 81% and 67% of the monocrop soybean yield in C-S-C and S-S-C systems at Prosper, respectively (Fig. 2).

Seed oil and C concentrations of relayed soybean was not affected by the presence of PC, WC, or rye in C-S-C or S-S-C sequences despite their decreasing yield in both systems (Table 5). Similar results were reported by Gesch et al. (2014) where seed oil concentration was similar for soybean whether it was relay cropped with WC or produced as a monocrop.

Soybean seed N concentration across Iowa and Minnesota sites was slightly reduced with a rye cover crop and at later seeding date (R8) in the S-S-C system. Oil and C concentrations of soybean seed across all cover crop treatments in both the cropping sequences averaged around 212 and 534 g kg^{-1}, respectively, and was similar to the no cover crop control (Table 5). At Prosper site, soybean seed quality was not affected by any treatments when relay intercropped with PC, WC, or rye cover crops (table 6). This suggest that even though the yield of soybean in double- and relay cropping systems was reduced, the quality of soybean seed was not affected.

Year Three Corn Yield and Quality

Field pennycress and WC, when used as oilseed crops, may result in seed accumulation in the soil seed bank l due to shattering losses before or at harvest. Field pennycress seed can remain dormant in soil for an extended period (Saini et al., 1987; Francis and Warwick, 2009; Karimmojeni et al., 2014) and may germinate and emerge the following spring at the time of row crop seeding or emergence. These volunteer oilseeds in the subsequent spring may provide competition to the row crop and negatively affect row crop growth, seed yield, and quality. In our study, despite some emergence of volunteer PC in the following spring (data not shown), the grain yield of Year 3 corn from both crop sequences was not affected by cover crop species, seeding date, or their interaction (Table 5 and 6). The mean yield of corn in both sequences was 12.8 Mg ha-1 across Iowa and Minnesota sites (Table 5). Whereas at Prosper, average corn yield was 12.4 and 13.5 Mg ha-1 for C-S-C and S-S-C systems, respectively (Table 6). Similar to soybean, seed N and C concentrations of year three corn were not affected by cover crop species, seeding date, or their interaction and averaged about 13 and 453 g kg^{-1}, across all sites, respectively.

Conclusions

Results document that soil moisture at oilseed cover crop harvest was not affected by WC or PC, indicating that moisture requirements of soybean would not be affected when relayed into these oilseed crops. When interseeded into standing corn and soybean, PC produced greater yield compared with WC. Seeding at later reproductive stages of corn and soybean, increased the oilseed yield of both PC and WC, suggesting late seeding of oilseed cover crops in the fall is preferred. Although when seeded later in the fall PC and WC produced greater seed yield, the seed yield of soybean was decreased when relayed into PC and WC in the C-S-C system. Despite some seed dormancy and emergence of volunteer PC in the spring following relay soybean harvest, there were no residual effects on the corn yields in the year following relay soybean harvest. There are several challenges in successfully integrating PC and WC into corn and soybean systems in the upper Midwest. As per the findings of our study, seeding at late reproductive stages or after harvest as suggested by Berti et al. (2017b) provides better chances for successful intercropping of PC and WC into corn or soybean and should improve system productivity.

Acknowledgments

This research was supported by a grant funded by USDA-National Institute of Food and Agriculture-Coordinated Agricultural Program (Award number: 2016-69004-24784). We are grateful for field and technical support provided by Alex Hard, Chuck Hennen, Dahlia Whiting, Dean Peterson, Grace Laskey, Janeille Schaubhut, Jay Hanson, Jim Eklund, Joe Boots, Luke Hodenfield, Matt Thom, Scott Larson, Taylir Bullick, Paula Peterson, and Roger Hintz.

References

Abendroth, L.J., R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. Publ. PMR-1009. Iowa State Univ. Ext. https://store.extension.iastate.edu/product/Corn-Growth-and-Development. (accessed 12 February 2020)

Appelgate, S.R., A.W. Lenssen, M.H. Wiedenhoeft, and T.C. Kaspar. 2017. Cover crop options and mixes for upper Midwest corn-soybean systems. Agron J. 109:968-984.

Basche, A.D., S.V. Archontoulis, T.C. Kaspar, D.B. Jaynes, T.B. Parkin, and F.E. Miguez. 2016. Simulating long-term impacts of cover crops and climate change on crop production and environmental outcomes in the Midwestern United States. Agric. Ecosyst. Environ. 218:95-106.

Bishop, L., and K.A. Nelson. 2019. Field pennycress seeding date and corn herbicide management effects on corn, pennycress, and soybean production. Agron. J. 111:257-263.

Berti, M., R. Gesch., B. Johnson, Y. Ji, W. Seames, and A. Aponte. 2015. Double-and relay-cropping of energy crops in the northern Great Plains, USA. Ind. Crop. Prod. 75:26-34.

Berti, M.T., B.L. Johnson, D. Ripplinger, R.W. Gesch, and A. Aponte. 2017a. Environmental impact assessment of double- and relay-cropping with winter camelina in the northern Great Plains, USA. Agricultural Sys. 156C:1-12

Berti, M.T., R.W. Gesch, C. Eynck, J. Anderson, and S. Cermak. 2016. Camelina uses, genetics, genomics, production and management. Ind. Crops Prod. 94:690-710.

Berti, M., D. Samarappuli, B.L. Johnson, and R.W. Gesch. 2017b. Integrating winter camelina into maize and soybean cropping systems. Ind. Crop. Prod. 107:595-601.

Blanco-Canqui, H. M. Sindelar, C.S. Wortman, and G. Kreikemeier. 2017. Aerial interseeded cover crop and corn residue harvest: Soil and crop impacts. Agron. J. 109:1344–1351.

Board, J.E., 1985. Yield components associated with soybean yield reductions at nonoptimal planting dates. Agron. J. 77:135-140.

Crookston, R.K., J.E. Kurle, P.J. Copeland, J.H. Ford, and W.E. Lueschen. 1991. Rotational cropping sequence affects yield of corn and soybean. Agron. J. 83:108-113.

Cubins, J.A. M.S. Wells, K. Frels, M.A. Ott, F. Forcella, G. Johnson, M.K. Walia, R.L. Becker, and R. Gesch. 2019. Management of pennycress as a winter annual cash cover crop. A review. Agron Sust. Develop. 39 (46) doi:10.1007/s13593-019-0592-0

Dabney, S.M., J.A. Delgado, and D.W. Reeves. 2001. Using winter cover crops to improve soil and water quality. Commun. Soil Sci. Plant Anal. 32:1221–1250.

Dose, H.L., C.A. Eberle, F. Forcella, and R.W. Gesch. 2017. Early planting dates maximize winter annual field pennycress (*Thlaspi arvense* L.) yield and oil content. Ind. Crop. Prod. 97:477-483.

Duncan, S.R., and W.T. Schapaugh, Jr. 1997. Relay-intercropping soybean in different water regimes, planting patterns, and winter wheat cultivars. J. Prod. Agric. 10:123–129.

Eberle, C.A., M.D. Thom, K.T. Nemec, F. Forcella, J.G. Lundgren, R.W. Gesch, W.E. Riedell, S.K. Papiernik, A. Wagner, D.H. Peterson, and J.J. Eklund. 2015. Using pennycress, camelina, and canola cash cover crops to provision pollinators. Ind. Crop Prod. 75:20-25.

Francis, A., and S.I. Warwick. 2009. The biology of Canadian weeds. 142. Camelina alyssum (Mill.) Thell.; C. microcarpa Andrz. ex DC.; C. sativa (L.) Crantz. Can. J. Plant Sci. 89(4):791-810.

Gesch, R.W., and S.C. Cermak. 2011. Sowing date and tillage effects on fall-seeded camelina in the northern Corn Belt. Agron. J. 103:980-987.

Gesch, R.W., D.W. Archer, and M.T. Berti 2014. Dual cropping winter camelina with soybean in the northern corn belt. Agron. J. 106:1735-1745.

Gesch, R.W., H.L.Matthees, A.L. Alvarez, and R.D. Gardner. 2018. Winter camelina: Crop growth, seed yield, and quality response to cultivar and seeding rate. Crop Science. 58(5):2089-2098.

Hexen, R.W., and R.F. Boxley. 1986. Trends in double cropping. Natural resource economics division, Economic Research Service, U. S. Department of Agriculture Agric. Econ. Rep. Num. p. 553.

Johnson, G.A., M.S. Wells, K. Anderson, R.W. Gesch, F. Forcella, and D.L. Wyse. 2017. Yield tradeoffs and nitrogen between pennycress, camelina, and soybean in relay-and double-crop systems. Agron. J. 109:2128-2135.

Jones, M.J., and M. Singh. 2000. Long-term yield patterns in barley-based cropping systems in northern Syria. 3. Barley monocropping. J. Agric. Sci. 135:251-259.

Karimmojeni, H.T., A. Taab, B. Rashidi, and A.H. Bazrafshan. 2014. Dormancy breaking and seed germination of the annual weeds *Thlaspi arvense*, *Descurainia sophia* and *Malcolmia africana* (Brassicaceae), J. Plant Protect. Res. 54:179–187.

Kaspar, T.C., J.K. Radke, and J.M. Laflen. 2001. Small grain cover crops and wheel traffic effects on infiltration, runoff, and erosion. J. Soil Water Conserv. 56:160–164.

Kladivko, E.J., T.C. Kaspar, D.B. Jaynes, R.W. Malone, J. Singer, X.K. Morin, and T. Searchinger. 2014. Cover crops in the upper midwestern United States: Potential adoption and reduction of nitrate leaching in the Mississippi River Basin. J. Soil Water Conserv. 69:279-291.

Kline, A.M., M.M. Scott, V.J. Tony, W.D. Terry, and C.P. Ellsworth. 2003. Management considerations for relay intercropping: I. Wheat. bull. no. AY315 Cooperative Ext. Serv, Purdue Univ. Agronomy Guide, Purdue, IN.

Laloy, E. and C.L. Bielders. 2010. Effect of intercropping period management on runoff and erosion in a maize cropping system. J. Environ. Qual. 39:1001-1008.

Mohammed Y.A., H.L. Matthees, R.W. Gesch, S. Patel, F. Forcella, K. Aasand, N. Steffl, B.L. Johnson, M. S. Wells, A.W. Lenssen. 2020. Establishing winter annual

cover crops by interseeding into maize and soybean. Agron. J. 2020:1-14 https://doi.org/10.1002/agj2.20062

Moore, K. J., and P. M. Dixon. 2015. Analysis of combined experiments revisited. Agron. J. 107:763-771. doi:10.2134/agronj13.0485

Munawar, A., R.L. Blevins, W.W. Frye, and M.R. Saul. 1990. Tillage and cover crop management for soil conservation. Agron. J. 82:773–777.

Myers, R.J.K., C.A. Palm, E. Cuevas, I.U.N. Gunatilleke, and M. Brossard. 1994. The synchronization of nutrient mineralization and plant nutrient demand. pp. 81-116 *In* P.L. Woomer and M.J. Swift (eds.) The Biological Management of Tropical Soil Fertility. John Wiley and Sons, New York.

Noland, R. L., M.S. Wells, C.C. Sheaffer, J.M. Baker, K.L. Martinson, and J.A. Coulter. 2018. Establishment and function of cover crops interseeded into corn. Crop Sci. 58(2):863-873

Ott, M.A., C.A. Eberle, M.D. Thom, D.W. Archer, F. Forcella, R.W. Gesch, and D.L. Wyse. 2019. Economics and agronomics of relay-cropping pennycress and camelina with soybean in Minnesota. Agron. J. 111:1281-1292.

Patel, S., J.E. Sawyer, and J.P. Lundvall. 2019. Can management practices enhance corn productivity in a rye cover crop system? Agron. J. 111:3161-3171.

Peterson, A., D. Samarappuli, and M.T. Berti. 2019. Intersowing cover crops into standing soybean in the US Upper Midwest. Agronomy 9: 264 http://dx.doi.org/10.3390/agronomy9050264

Plastina, A., F. Liu, F. Miguez, and S. Carlson. 2018. Cover crops use in Midwestern US agriculture: perceived benefits and net returns. Renew. Agric. Food Syst. 35:38-48.

Power, J.F., and R.F. Follett. 1987. Monoculture. Scientific Amer. 256:78-87.

Raimbult, B.A., T.J. Vyn, and M. Tollenaar. 1991. Corn response to rye cover crop, tillage methods, and planter options. Agron. J. 83:287– 290.

Reganold, J.P., R.I. Papendick, and J.F. Parr. 1990. Sustainable agriculture. Scientific Amer. 262:112-121.

Reinbott, T.M., Z.R. Helsel, D.G. Helsel, M.R. Gebhardt, and H.C. Minor. 1987. Intercropping soybean into standing green wheat. Agron. J. 79:886-891

Royo-Esnal, A., J. Necajeva, J. Torra, J. Recasens, and R.W. Gesch. 2015. Emergence of field pennycress (*Thlaspi arvense* L.): comparison of two accessions and modelling. Ind. Crop Prod. 66:161-169.

Saini, H.S., P.K. Bassi, J.S. Goudey, and M.S. Spencer. 1987. Breakage of seed dormancy of field pennycress (*Thlaspi arvense*) by growth-regulators, nitrate, and environmental-factors. Weed Sci. 35:802-806.

Sainju, U.M., B.P. Singh, and W.F. Whitehead. 2002. Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. Soil Tillage Res. 63:167–179.

Wallace, S.U., M. Bacanamwo, J.H. Palmer, and S.A. Hull. 1996. Yield and yield components of relay-intercropped wheat and soybean. Field Crop. Res. 46: 161–168.

Wells, M.S., S.C. Reberg-Horton, and S.B. Mirsky. 2014. Cultural strategies for managing weeds and soil moisture in cover crop based no-till soybean production. Weed Sci. 62:501-511.

Wright, D., and A.W. Lenssen. 2013. Staging soybean development. Agric. Env. Ext. Pub. 191. http://lib.dr.iastate.edu/extension_ag/pubs/191 (accessed 12 February 2020).

Figures and Tables

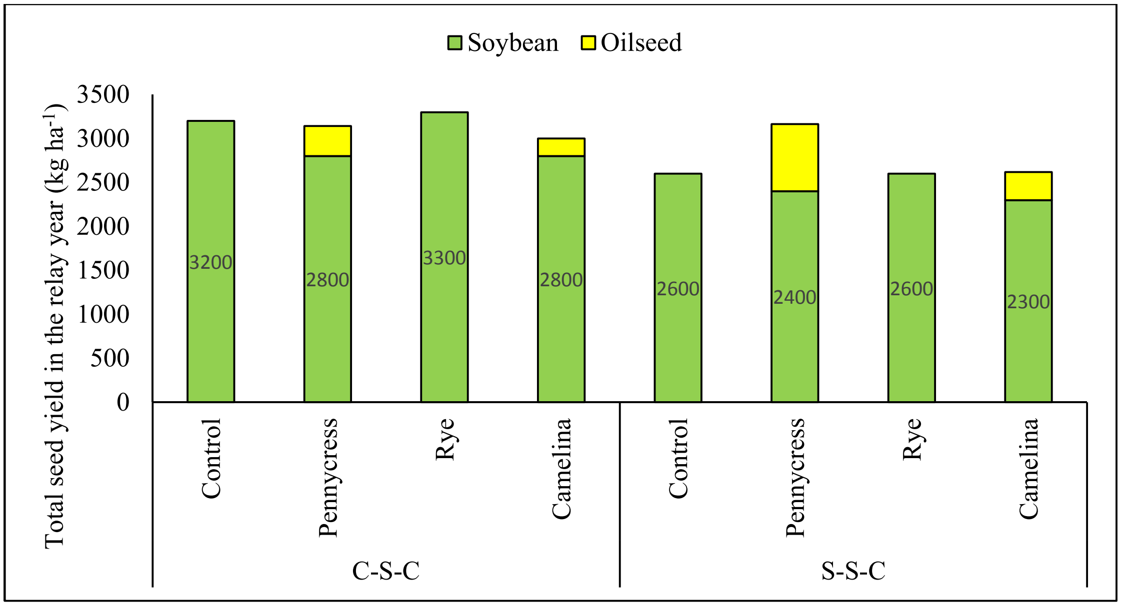

Fig. 1. Total grain yield (soybean and oilseed cover crop) in relay year for 2018 and 2019 in corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C) sequences across sites (Ames, IA; Morris, and Rosemount, MN).

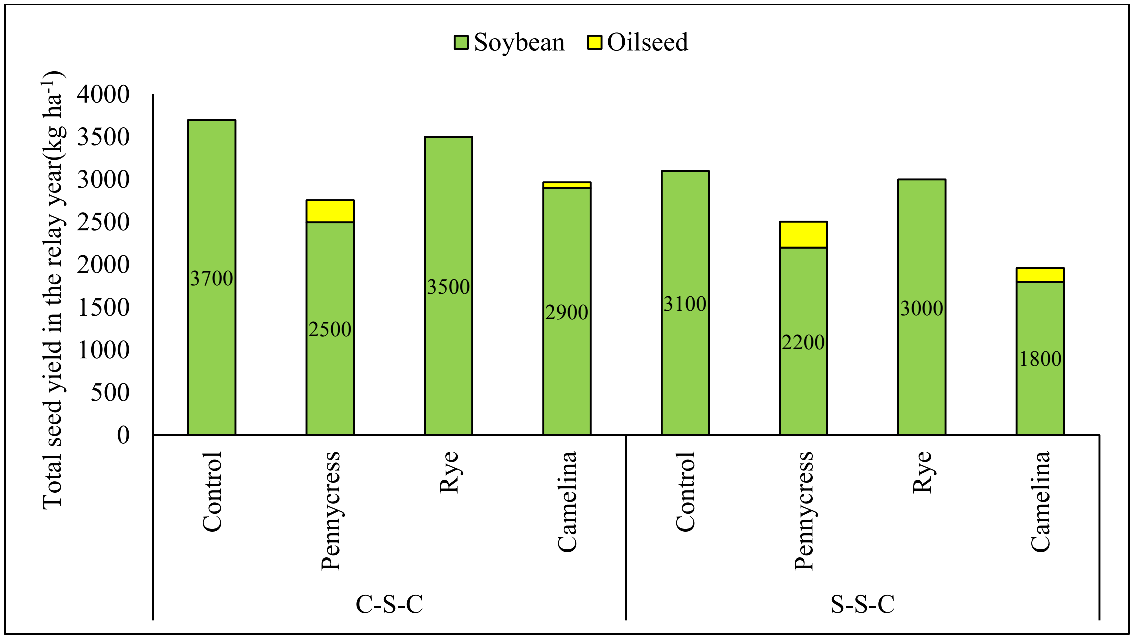

Fig. 2. Total grain yield (soybean and oilseed cover crop) in relay year for 2018 and 2019 in corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C) sequences at Prosper, ND.

Table 1. Cover crop, soybean and corn planting and harvest dates in corn-soybean-corn and soybean-soybean-corn sequences. in Ames, IA, Morris and Rosemount, MN, and Prosper, ND in 2017, 2018 and 2019.

Field Operation	Ames	Morris	Rosemount	Prosper
Cover crop interseeding in to standing corn				
R4	09 Aug. 2016; 11 Aug. 2017	23 Aug. 2016; 23 Aug. 2017	29 Aug. 2017	19 Aug. 2016; 24 Aug. 2017
R5	01 Sep. 2016; 08 Sep. 2017	02 Sep. 2016; 07 Sep. 2017	12 Sep. 2017	06 Sep. 2016; 06 Sep. 2017
R6	29 Sep. 2016; 25 Sep. 2017	14 Sep. 2016; 22 Sep. 2017	20 Sep. 2017	22 Sep. 2016; 19 Sep. 2017
Relay soybean planting following previous year corn	09 May 2017; 11 May 2018	05 May 2017; 15 May 2018	04 June 2018	12 May 2017; 23 May 2018
Cover crop harvest interseeded in to standing corn				
R4; R5; R6 (PC)	12 June 2017; 10 June 2018	R4 15 June, R5 and R6 19 June 2017; 29 June 2018	N/A	R5 16 June and R6 21 June 2017; 22 June 2018
R4; R5; R6 (WC)	20 June 2017; 16 June 2018	R4 27 June, R5 and R6 30 June 2017; R4 2 July and R5 and R6 3 July 2018	N/A	R5 27 June, R6 7 July 2017; 9 July 2018
Rye termination	04 May 2017; 08 May 2018	7 June 2017; 11 May 2018	01 June 2018	5 May 2017; 21 May 2018
Relay soybean harvest	18 Oct. 2017; 10 Oct. 2018	10 Oct. 2017; 23 Oct. 2018	22 Oct. 2018	19 Oct 2017; 22 Oct 2018
Year 3 corn planting	13 May 2018; 03 May 2019	16 May 2018; 15 May 2019	23 May 2018	15 May 2018; 29 May 2019
Year 3 Corn harvest	15 Oct 2018; 09 Oct. 2019	16 Oct. 2018; 30 Oct. 2019	09 Oct. 2019	31 Oct 2018; 5 Nov 2019
Cover crop interseeding in to standing soybean				
R6	18 Aug. 2016; 24 Aug. 2017	23 Aug. 2016; 23 Aug. 2017	29 Aug. 2017	19 Aug. 2016; 24 Aug. 2017
R7	12 Sep. 2016; 15 Sep. 2017	02 Sep. 2016; 07 Sep. 2017	12 Sep. 2017	06 Sep. 2016; 06 Sep. 2017
R8	30 Sep. 2016; 25 Sep. 2017	14 Sep. 2016; 22 Sep. 2017	20 Sep. 2017	22 Sep. 2016; 19 Sep. 2017
Relay soybean planting following previous year soybean	09 May 2017; 11 May 2018	05 May 2017; 15 May 2018	04 June 2018	12 May 2017; 23 May 2018
Cover crop harvest interseeded in to standing soybean				
R6; R7; R8 (PC)	12 June 2017; 09 June 2018	15 June 2017; 29 June2018	22 June 2018	R7 16 June and R8 21 June 2017; 22 June 2018
R6; R7; R8 (WC)	21 June 2017; 15 June 2018	19 June 2017; 05 July 2018	11 July 2018	R7 27 June, R8 7 July 2017; 9 July 2018
Rye termination	06 May 2017, 08 May, 2018	7 June 2017; 18 May 2018	01 June 2018	5 May 2017; 21 May 2018
Relay soybean harvest	18 Oct. 2017; 10 Oct. 2018	10 Oct. 2017; 23 Oct 2018	22 Oct 2018	19 Oct 2017; 22 Oct 2018
Year 3 corn planting	13 May 2018, 03 May 2019	16 May 2018; 15 May 2019	23 May 2019	15 May 2018; 29 May 2019
Year 3 corn harvest	15 Oct. 2018; 09 Oct. 2019	16 Oct. 2018; 30 Oct. 2019	9 Oct. 2019	31 Oct 2018; 5 Nov 2019

R4, R5, R6 and R6, R7, R8 are developmental stages of corn and soybean respectively for cover crop seeding.

Table 2. Monthly mean air temperature (°C) and total rainfall (cm) in 2017, 2018, 2019, and long-term average across three sites (Ames, IA; Morris and Rosemount, MN) and Prosper, ND.

Month	Average across sites								Prosper							
	2017		2018		2019		LTA		2017		2018		2019		LTA	
	Tem[‡]	RF[§]	Tem	RF	Tem	RF	Tem	RF	Tem	RF	Tem	RF	Tem	RF	Tem	RF
Jan.	-6.9	3.7	-9.5	2.1	-10.6	1.2	-9.7	2.1	-11.3	M	-13.0	M	-15.3	M	-13.1	1.5
Feb.	-0.8	1.9	-10.0	2.6	-12.5	4.7	-7.2	2.1	-5.3	M	-15.3	M	-18.9	M	-10.0	1.4
Mar.	0.6	3.6	-0.3	3.5	-3.2	5.0	0.1	4.8	-2.5	M	-5.2	M	-8.8	M	-2.7	2.9
Apr.	9.3	8.6	2.7	3.6	7.9	8.0	8.3	7.8	6.6	1.7	0.0	0.4	5.0	2.3	6.3	3.7
May	14.4	14.4	19.0	7.9	12.8	16.3	15.0	10.1	13.2	1.7	16.9	5.4	10.7	6.0	13.4	7.7
June	21.1	7.9	21.8	17.8	20.5	8.5	20.3	11.7	19.1	8.8	20.5	7.9	19.2	12.2	18.7	10.0
July	22.9	6.2	20.5	8.9	23.0	13.6	22.3	10.9	21.2	5.0	20.3	6.5	21.9	15.6	21.3	8.8
Aug.	19.4	13.0	16.3	13.0	20.2	8.8	16.1	10.8	18.1	5.3	19.4	7.9	18.4	10.2	20.4	6.7
Sep.	18.3	6.4	10.8	11.7	18.6	14.7	16.6	8.2	15.3	15.2	14.1	7.1	15.5	14.8	14.8	6.6
Oct.	10.3	10.7	3.5	8.1	7.3	9.1	9.5	6.5	7.5	0.7	3.8	6.7	4.6	7.7	7.3	6.2
Nov.	0.5	0.7	5.8	7.2	-10.6	1.2	0.7	4.1	-3.3	M	-6.1	M	M	M	-1.9	2.3
Dec.	-7.0	0.7	5.1	8.6	-12.5	4.7	-7.1	2.6	-11.2	M	-8.0	M	M	M	-10.1	1.6

[†] LTA = Long term average, [‡] Tem= mean air temperature; [§] RF= total monthly rainfall; and [¶] M = missing data

Table 3. Pennycress (PC) and camelina (WC) seed yield and quality in three seeding dates (SD1, SD2, and SD3) across sites (Ames, IA; Morris, and Rosemount, MN) for year 2017 and 2018 in corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C) sequences.

	C-S-C sequence				S-S-C sequence			
Treatment (Cover)[†]	Yield	Oil	N	C	Yield	Oil	N	C
	kg ha^{-1}	—— g kg^{-1}——			kg ha^{-1}	—— g kg^{-1}——		
PC1	325.4	272	41	533	658.7	279	41	534
PC2	304.0	287	42	545	749.1	303	41	546
PC3	401.5	285	43	546	879.7	293	42	552
WC1	64.9	308	44	548	42.1	297	45	515
WC2	209.0	311	44	547	143.3	331	42	500
WC3	328.0	327	44	551	770.0	344	45	556
SE	91.1[‡]	20.6	1.5	14.6	295.5	12.6	1.8	22.9
	$P > F$							
PC vs WC	**	***	**	NS	*	**	NS	NS
SD1 vs SD2	NS	NS	NS	NS	NS	*	NS	NS
SD1 vs SD3	**	NS	NS	NS	*	*	NS	NS
SD2 vs SD3	NS	NS	NS	NS	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

[†] Treatments PC1 to PC3 are pennycress treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively. Treatments WC1 to WC3 are camelina treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively

[‡] Indicates weighted SE for all variables.

Table 4. Treatment means and significance for pennycress (PC) and camelina (WC) seed yield in three seeding dates (SD1, SD2, and SD3) in 2017 and 2018 and seed quality in S-S-C sequence in 2018 for Prosper, ND site.

	C-S-C	S-S-C			
Treatment (Cover)†	Yield	Yield	Oil	N	C
	kg ha^{-1}	kg ha^{-1}	———— g kg^{-1}		————
PC1	218.8	251.0	318	41	556
PC2	242.0	281.9	323	40	558
PC3	316.9	385.9	321	40	556
WC1	15.4	120.8	383	47	585
WC2	30.6	136.5	387	47	587
WC3	158.5	230.9	385	46	582
SE	149.52‡	126.58	3.4	0.6	1.0
		P > F			
PC vs WC	NS	*	***	***	***
SD1 vs SD2	NS	NS	NS	NS	NS
SD1 vs SD3	NS	NS	NS	NS	NS
SD2 vs SD3	NS	NS	NS	NS	**
Cover × SD	NS	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively [†]Treatments PC1 to PC3 are pennycress treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively. Treatments WC1 to WC3 are camelina treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively

[‡]Indicates weighted SE for all variables.

Table 5. Treatment means and significance for soil moisture at cover crop harvest, soybean measurements including seed yield, silicles plant-1(Sil), nodes plant-1, plant height (Ht), seed oil, seed N, and seed C concentrations, and Year 3 corn grain yield, seed N and C concentration across sites (Ames, Morris, Rosemount) and years (2017 and 2018) for corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C) rotations, respectively. Corn grain N and C is only presented for year 2018.

	Soil moisture		Relay soybean							Year 3 Corn		
Treatment†	0-30 cm	30-60 cm	Nodes	Sil	Ht	Yield	Oil	N	C	Yield	N	C
	— g kg^{-1} —		–# plant^{-1}–		cm	Mg ha^{-1}	—— g kg^{-1}——			Mg ha^{-1}	– g kg^{-1}–	
					C-S-C							
Control	216	208	13.2	28.9	80.2	3.2	211	63	534	12.8	12	453
PC1	192	203	13.0	29.7	70.0	2.5	211	63	533	12.8	12	453
PC2	189	201	12.9	30.4	73.8	2.9	213	63	534	12.8	12	453
PC3	190	197	13.3	31.8	75.8	3.0	213	62	534	12.6	12	453
Rye1	209	205	13.4	30.4	79.1	3.2	211	63	534	12.7	12	453
Rye2	192	195	13.3	30.0	79.6	3.3	211	63	534	13.2	12	453
Rye3	183	196	13.4	30.2	81.8	3.3	212	63	535	12.8	12	453
WC1	193	210	12.9	29.5	77.7	2.8	211	63	534	13.3	12	452
WC2	185	202	12.7	28.9	74.3	2.7	215	63	534	12.4	12	453
WC3	194	203	12.8	29.3	74.8	2.8	212	63	534	12.7	12	452
SE	19.2‡	18.1	1.6	6.17	8.29	0.29	4.1	0.7	1.7	0.65	1.2	3.5
					$P > F$							
Control vs. PC	NS‡	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs. WC	NS	NS	NS	NS	NS	*	NS	NS	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
					S-S-C							
Control	197	198	13.4	30.2	74.1	2.6	211	65	534	12.4	12	451
PC1	183	197	13.0	29.0	66.5	2.3	212	64	533	13.1	13	452
PC2	187	199	13.3	29.7	64.0	2.3	211	64	534	13.2	12	452
PC3	185	196	13.2	29.1	66.2	2.5	213	64	534	13.4	12	452
Rye1	197	202	13.3	30.6	73.5	2.6	213	64	535	12.6	12	452
Rye2	187	204	13.1	27.3	68.8	2.6	212	64	534	13.3	13	452
Rye3	185	201	13.8	30.5	74.9	2.6	213	64	534	12.8	12	452
WC1	191	205	12.9	28.1	70.2	2.3	211	65	533	12.9	13	452
WC2	186	202	12.1	25.8	64.0	2.2	213	64	534	12.8	12	452
WC3	197	210	13.1	29.5	66.7	2.4	212	64	533	12.4	13	452
SE	13.3	17.1	1.24	2.52	5.23	0.27	2.8	1.2	1.2	0.70	1.1	4.5
					$P > F$							
Control vs. PC	NS	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS	NS
Control vs. WC	NS	NS	*	NS	**	NS	NS	NS	NS	NS	NS	NS
Control vs. SD1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs. SD2	NS	NS	NS	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. SD3	NS	NS	NS	NS	*	NS	NS	*	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

†Control treatment with no cover crop. PC1-PC3 are pennycress cover crop treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively. Rye1-Rye3 are rye cover crop treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively and treatments WC1-WC3 are camelina cover crop treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively.

‡Indicates weighted SE for all variables.

Corn and soybean yields are expressed at 155 and 130 g kg^{-1} moisture, respectively. Soil moistures are expressed on an oven-dry basis.

Table 6. Treatment means and significance for soil moisture at cover crop harvest and soybean measurements including grain yield (Y), silicles (Sil), node count (Nodes), plant height (Ht), seed oil, seed N, and seed C and year 3 corn yield (Y), seed N and C concentration across years (2017 and 2018) at Prosper, ND site for corn-soybean-corn (C-S-C) and soybean-soybean-corn (S-S-C) rotations, respectively. Corn grain N and C is only presented for year 2018.

	Relay soybean							Year 3 corn		
Treatment†	Nodes	Sil	Ht	Yield	Oil	N	C	Yield	N	C
	— plant^{-1}—		cm	Mg ha^{-1}	—— g kg^{-1}——			Mg ha^{-1}	— g kg^{-1}—	
				<u>C-S-C</u>						
Control	13.6	27.0	92.3	3.7	208	62	529	13.0	14	453
PC1	10.3	20.4	55.5	2.5	205	63	529	12.3	14	453
PC2	10.4	23.1	59.5	2.7	205	63	528	11.6	14	454
PC3	11.4	21.6	51.6	2.3	205	63	529	11.9	14	454
Rye1	13.1	28.5	88.8	3.5	208	62	529	12.8	15	454
Rye2	12.3	21.6	79.3	3.4	207	62	529	12.4	15	454
Rye3	12.9	26.3	84.2	3.7	208	61	529	13.0	14	453
WC1	10.5	25.4	49.9	2.7	208	61	529	12.7	15	454
WC2	11.3	28.2	54.2	3.0	206	62	528	12.4	14	454
WC3	10.2	21.4	50.2	2.9	205	62	528	12.1	14	454
SE	0.56‡	2.74	5.35	0.40	6.6	1.1	2.1	2.67	0.4	0.5
				P > F						
Control vs. PC	***	NS‡	***	*	NS	NS	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs. WC	***	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. SD1	***	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. SD2	***	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. SD3	**	NS	***	NS	NS	NS	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
				<u>S-S-C</u>						
Control	14.4	26.7	86.2	3.1	209	63	532	13.8	14	455
PC1	13.5	23.1	66.1	2.3	208	64	532	12.5	14	454
PC2	12.6	24.0	64.3	2.3	207	64	532	13.5	14	455
PC3	12.5	21.7	59.5	2.1	207	65	531	13.3	14	454
Rye1	14.4	29.7	80.5	3.2	208	63	532	13.5	15	454
Rye2	14.5	30.6	78.2	2.9	208	63	530	13.1	15	454
Rye3	13.9	25.4	78.3	2.9	209	63	532	13.7	15	455
WC1	11.6	25.9	48.1	1.7	207	64	532	13.8	15	454
WC2	11.2	26.1	45.2	2.0	209	63	532	13.4	14	454
WC3	12.3	26.6	50.6	1.8	206	64	531	14.6	14	455
SE	0.49	2.78	4.52	0.38	6.5	1.1	2.5	1.91	0.4	0.5
				P > F						
Control vs. PC	*	NS	***	*	NS	NS	NS	NS	NS	NS
Control vs. Rye	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Control vs. WC	***	NS	***	**	NS	NS	NS	NS	NS	NS
Control vs. SD1	*	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. SD2	**	NS	***	NS	NS	NS	NS	NS	NS	NS
Control vs. SD3	*	NS	***	*	NS	NS	NS	NS	NS	NS
Cover × SD	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively

†Control treatment with no cover crop. PC1-PC3 are pennycress cover crop treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively. Rye1-Rye3 are rye cover crop treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively and treatments WC1-WC3 are camelina cover crop treatments seeded at R4, R5 and R6 and R6, R7 and R8 in corn and soybean, respectively

‡Indicates weighted SE for all variables.

Corn and soybean grain yields expressed at 155 and 130 g kg^{-1} moisture, respectively.

CHAPTER 4. MANAGEMENT, PRODUCTIVITY AND WEED COMMUNITY DYNAMICS IN CORN-ALFALFA INTERCROPPING IN IOWA

Swetabh Patel, Andrew W. Lenssen, Kenneth J. Moore and Marisol. T Berti

S. Patel, A.W. Lenssen, K.J. Moore, Dept. of Agronomy, Iowa State Univ., Agronomy Hall, Ames, IA 50011-1010, USA; M.T. Berti, Dept. Plant Sciences, North Dakota State Univ., Loftsgaard Hall, Fargo, ND 58102, USA.

Modified from a manuscript to be submitted to Agronomy Journal

Abstract

Intercropping of legumes with cereals for forage production is one of the most practical multi-cropping techniques to increase crop yield and improve land use efficiency. Intercropping alfalfa (*Medicago sativa* L.) with corn (*Zea mays* L.) has the potential to increase the overall economic yield, as well as improve land sustainability compared with either crop alone. The objective of this study was to increase the overall productivity and improve the resiliency of the cropping system. The study was conducted near Boone, Iowa in 2016-2018 and repeated in 2017-2019. Corn was planted in 76-cm rows and alfalfa were then drilled in between the corn rows on the same day. The experimental design was a randomized complete block design with four replications. Each block had 5 treatments: alfalfa only, corn only, corn intercropped with alfalfa, corn intercropped with alfalfa with prohexadione (PHD) applied to alfalfa at V8 corn stage, and spring seeded alfalfa (corn in the establishment year followed by planting alfalfa the following year). Corn grain yield was reduced by 23-26% when intercropped with alfalfa. Application of PHD to alfalfa did not affect corn grain yield or improve alfalfa establishment. Alfalfa stand density under corn canopy was reduced by 36-68% compared to alfalfa alone in the establishment year. There was no difference in alfalfa yield and quality in the second production year, however, intercropped alfalfa yield was 5-6 times greater than spring seeded alfalfa in the first production year.

Key words: corn; alfalfa; intercropping

Abbreviations: LAI; leaf area index; PHD, prohexadione calcium

Introduction

Multi-cropping techniques where legumes are intercropped with cereals for forage production is a practice to increase overall yield and improve land use efficiency (Zhang et al., 2011) Legume-cereal intercropping yields are consistently greater when compared with monoculture (Anil et al., 1998). Growing crops in mixed stands can be more productive than monocultures mainly because of better nutrient-use-efficiency, improved light use, enhanced weed control, pest suppression, and reduced water run-off (Anil et al., 1998; Zhang and Li, 2003).

Zhang et al. (2013) showed that intercropping alfalfa (*Medicago sativa* L.) with corn (*Zea mays* L.) resulted in greater grain production for corn and greater forage biomass production for alfalfa, as well as greater land sustainability compared with either crop alone. Pendleton et al. (1957) reported that early seeding of forage legumes into standing corn favored legume stand establishment. The best stands of alfalfa were obtained when seeded at the same time as corn.

In China, water infiltration rate was increased, and surface sediment run-off was decreased when alfalfa was intercropped or grown in rotation (Wu et al., 2011). The absence of tillage during the alfalfa phase of the rotation improves soil structure compared to tillage for an annual crop (Wu et al., 2011). In a conventional system, where corn is harvested and the soil tilled to prepare a seedbed for the subsequent spring alfalfa crop, the soil surface will be bare during the winter and early spring, increasing soil erosion and nutrient losses by run-off (Hatfield et al., 2009). Therefore, integrating alfalfa into the cropping system sooner can provide cover to the soil and improve the infiltration rate, thereby reducing surface run-off and soil sediment loss (Wu et al., 2011).

Light competition is an important factor in alfalfa-corn intercropping. Specifically, light interception by corn is about 80 to 90% at tasseling, thus, only 10% of photosynthetically active radiation (PAR) will be available for the alfalfa under the canopy (Matusso et al., 2014). The main drawbacks of corn–alfalfa intercropping with the lack of light for alfalfa plants growing under the corn canopy is the etiolation (longer internodes) of alfalfa stems, poor establishment of alfalfa under a dense corn canopy, and perhaps chances of increased disease and pest pressure. Intercropped alfalfa would likely compete with corn for nutrients, water and other resources and may decrease corn yield. In order to improve the survival of the alfalfa under the canopy and reduce stem etiolation, growth regulators have been evaluated to suppress internode elongation. Rethwisch et al. (2003) used prohexadione calcium [Apogee ® (BASF Corp., NJ, USA)], as a growth regulator in alfalfa for this purpose. Prohexadione (PHD) is a gibberellic acid inhibitor registered for use in other crops. It reduces internode elongation (Rademacher, 2000), resulting in increased alfalfa leaf/stem ratio and improved survival under the silage corn canopy (Grabber, 2016). Intercropped alfalfa treated with prohexadione in the seeding year competed less with the corn and improved the survival the survival rate of alfalfa intercropped with silage corn (Osterholz et al., 2018). First-year yields of alfalfa established as an intercrop with corn the previous year were two-fold greater than alfalfa spring-seeded after corn. In recent studies where prohexadione was used, first year alfalfa yields and fall stand densities were improved compared with untreated alfalfa (Grabber, 2016).

Alfalfa-corn based cropping systems improve N economy of the cropping system by adding N credits (Olmstead and Brummer, 2008), reducing subsequent corn N requirements

(Yost et al., 2013; Mikic et al., 2015), increasing productivity, and net returns in comparison with monoculture (Seran and Brintha, 2010). In a study conducted in Minnesota, alfalfa added 47 to 72 kg ha^{-1} of N credit to the corn silage crop, increasing corn silage yield 1.8 Mg ha^{-1}.

Considerable losses in crop production occur due to the presence of weeds that compete with the crop for nutrients, water, and light (Stephens, 1982). Alfalfa establishment stand density and overall productivity can be negatively affected by the presence of a number and types of weed species and overall weed biomass. Therefore, for successful production of alfalfa, accurate information regarding the presence and composition of the weed community is needed.

Low productivity of alfalfa in the seeding year and high risk of soil and nutrient loss associated with conventional corn provide an opportunity for using corn as a companion crop for alfalfa establishment. In a corn-alfalfa intercropping system corn would serve as a companion crop to alfalfa during establishment and alfalfa would serve as a cover crop after corn harvest, while also having potential to enhance productivity by bringing alfalfa into full forage production the following year. With the availability of glyphosate-tolerant corn and alfalfa, and the use of growth regulators (Osterholz et al., 2018), corn-alfalfa intercropping has potential in Iowa.

The objective of this study was to determine the overall productivity of a corn alfalfa intercropping system and identify the weed community present at various stages of alfalfa establishment and growth.

Materials and Methods

Site Description

A three-year corn-alfalfa intercropping study was started in 2016 at Sorenson research farm in Boone, IA (42°00'N, 93°44'W). The entire study was replicated in 2017 on a different field on the same research farm. Soil types for both locations were Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludolls) and Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquolls) (Web Soil Survey, 2009). Weather data including monthly precipitation and temperature along with long term weather history were obtained from a weather station (Ames-8-WSW) located nearby the experimental sites and reported by Iowa Environmental Mesonet Network (Herzmann, 2020). Soil pH, and available P and K levels were maintained based on the baseline soil test results obtained at the beginning of each study (Table 1).

Plot Design and Management

The experimental design was a randomized complete block with four replications. Each replication included five treatments: T1) alfalfa alone, T2) corn alone, T3) alfalfa interseeded into corn, T4) alfalfa interseeded into corn with an application of prohexadione (PHD) [calcium, 1-(4-carboxy-2, 6-dioxocyclohexylidene) propan-1-olate], and T5) spring seeded alfalfa check. Each plot was 7.62 × 3.05 m with either corn only, alfalfa only or 4 rows of corn and 16 rows of alfalfa seeded together on the same date. Corn (DeKalb DKC57-75RIB, 107 RM) was planted (80000 plants ha^{-1}) using a four-row planter (Kinze Manufacturing, Inc., Williamsburg, IA.) whereas glyphosate resistant alfalfa (Pioneer 54QR04 (RR); germination: 84%; hard seed: 3%; fall dormancy:4) was planted at 15 kg ha^{-1} PLS using a small seed grain drill (ALMACO, Nevada, IA). Prohexadione calcium, an anti-gibberellic hormone, was applied at a rate of 0.5 kg a.i. ha^{-1} over the alfalfa, but under the corn canopy when corn was at V8 (Abendroth et al., 2011) and alfalfa at 20-cm height. The PHD solution was prepared using ammonium sulfate (1.12 kg ha^{-1}), citric acid (0.94 kg ha^{-1}), and crop oil concentrate (2.3 l ha^{-1}) with water and was applied at 187 L ha^{-1}. Dates of corn, alfalfa planting, and application of PHD are presented in Table 2. EPTC (S-ethyldipropylthiocarbamate) at 6.35 kg a.i. ha^{-1} (applied preplant) along with glyphosate (isopropylamine salt of N-(phosphonomethyl)glycine) at the rate of 0.84-0.91 kg a.e.

ha^{-1} was used to control weeds. All the plots were fertilized before planting by broadcasting 168-112-100 kg ha^{-1} of N-P-K in the form of urea, diammonium phosphate, and muriate of potash. Alfalfa plots were sprayed with dimethoate (0,0-dimethyl-S-[N-methylcarbamoyl) methyl] phosphorodithioate) at 585 mL a.i. ha^{-1} twice in the establishment year and three times in the full production year to control potato leafhoppers (*Empoasca fabae* Harris).

Data Collection and Analysis

Soil sampling

At the start of each experiment in 2016 and 2017, baseline soil samples (0-15 cm depth) were collected across each replicate (composite of six cores) and analyzed for pH, organic matter, P (Olsen) and K (Mehlich-3). Additional soil samples (composite of three cores) were also collected from each plot from 0-15 and 15-60 cm depth in late fall of the establishment year of each experiment following corn harvest. The available soil P and K were determined using the Olsen method and the Mehlich-3 tests, respectively (Franzen, 2010), whereas soil NO_3-N concentration was determined by the transnitration of salicylic acid method (Cataldo et al., 1975). Baseline soil test results are shown in Table 1. All soil samples were analyzed by the North Dakota State Soil testing lab.

Corn Early Growth, Population, and Harvest

At the time of PHD application, R1 corn developmental stage and before harvest, corn leaf area index (LAI) measurements were collected using a Decagon AccuPAR leaf area meter (Decagon Devices Inc., Pullman, WA). Four readings of LAI were collected from the middle two rows and averaged to calculate LAI for each plot. Corn plant height at PHD application and before harvest was determined by measuring height (ground to extended top leaf tip) from five random plants in the middle two rows of each plot. Corn plant density (plants ha^{-1}) was also measured at PHD application and before harvest. In each plot, plants from one linear m were cut

6-8 cm from the ground and fresh weight was recorded. After weighing the plants, two corn plants were selected, weighed separately (fresh weight) and then placed in a dryer until a constant weight was achieved. Once dried, the whole plant was weighed, and the harvest index was calculated by weighing the grain separately:

HI = corn grain yield (kg DM ha^{-1}) / corn biomass yield (kg DM ha^{-1}). [Eq. 1].

Corn grain yield was determined by harvesting two center rows in each plot using a John Deere 9450 combine and the yield was reported at 15.5% moisture.

Alfalfa growth measurements and harvest

In each plot a 1-m^2 area was marked from which alfalfa was hand harvested for dry matter determination, then the remainder of the plot was mowed, and forage removed. In the establishment year, alfalfa was manually harvested once from a 1 m^2 area in each plot before corn was harvested for grain with a combine. In the first and second full production year of alfalfa, four cuttings were manually harvested from 1 m^2 area in each plot. However, spring planted alfalfa was only harvested twice in the year it was seeded. Alfalfa biomass samples were placed in a paper bag and dried in a forced air drier at 49 ^{o}C for 5 days and then weighed. Targeted harvest stage for alfalfa cuttings were early bud for first cutting, 10% bloom for the second cutting, and 20-30% bloom for cuttings three and four. Alfalfa was not harvested if stem height was shorter than 40.6 cm. Dates of alfalfa cutting over the years are presented in Table 3.

At each harvest of alfalfa, random measurements from each plot were taken to estimate the mean stem height and alfalfa growth stage was determined according to Kalu and Fick (1983). Stem density of alfalfa was also measured at each harvest by counting the total number of stems in 1-m^2 within the same harvest area from each plot.

Forage quality analysis

Alfalfa biomass samples were dried and grounded in a cyclone mill (UDY Corp., Ft. Collins, CO) to pass through a 1 mm screen and then analyzed for total N, ash content, lignin, and neutral detergent fiber digestibility (NDFD). Crude protein (CP) was estimated as total N x 6.25. Forage quality was only analyzed for alfalfa biomass samples from the first and second years of alfalfa production. Samples were analyzed in a laboratory at North Dakota State University using a calibrated NIRS XDS analyzer (FOSS Analytical, Hillerød, Denmark).

Weed community and density

Weed density and type of weed community was assessed in the establishment year at the time of corn harvest and in the first and second production year of alfalfa. Each year weed data were collected before the first in-season herbicide application or at first harvest of alfalfa as well as in fall before last harvest of alfalfa by counting the total number of weeds and plants per species from five randomly thrown 0.1-m^2 circular quadrats. Total weed density and weed density for each species per square meter were determined by multiplying with a factor of two.

Statistical Analysis

Analysis of variance and mean comparisons were conducted using the Mixed Procedure of SAS (SAS Institute Inc., 2014). Years and treatments were considered fixed while blocks were considered random. Mean comparisons were performed at the $P \leq 0.05$ probability level. Due to the observed variability in experimental years, data were analyzed separately for each year. Contrast statements were used to make specific pairwise comparisons.

Results and Discussion

Weather Conditions

Temperature and precipitation in spring are important for timely planting of the crops and their subsequent emergence and growth. Mean temperature in 2017 and 2018 spring (March-

May) was similar to the 30-year mean whereas it was slightly above in 2016 and 1.3 °C below in 2019. Total spring precipitation in 2017 and 2018 was 4 and 7.6-cm above and below the long-term trailing mean, respectively. April and May 2018 were considerably drier than the long-term mean, and the total accumulated precipitation was 9 cm below the norm. Summer temperature (June-Aug.) throughout the experimental years did not deviate from the long-term mean, however, summer of 2017 and 2019 was very dry receiving 22 and 12-cm less rainfall than the long-term mean, respectively. June and August in 2018 were very wet and received an excess precipitation of 15 and 9 cm, respectively. Fall temperatures (Sept.-Nov.) in 2016 and 2017 were slightly warmer than the long-term mean and 1°C below it in 2018. Fall precipitation was excessive in all experimental years except 2017. Precipitation in excess of 7, 14, and 9-cm was received in fall of 2016, 2018, and 2019, respectively. Mean winter temperatures (Dec.-Feb.) were similar to the long-term trailing mean except in 2017 which was 4°C warmer. Overall winter precipitation through snow and rainfall accumulation did not vary greatly but was in excess of 6-cm in 2018.

Corn Leaf Area Index, Plant Height and Population

In the study started in 2016, leaf area index (LAI) measurement collected at early vegetative stage of corn (V8) at the time of PHD application was slightly lower in the corn intercropped with alfalfa (Table 5) suggesting initial stress on corn growth due to the presence of alfalfa. However, at later stages of corn growth (R1 and pre-harvest) differences in the LAI between the intercropped and corn only treatments were not present. There was no difference in corn plant height and plant population density at PHD application. However, in 2016 plant height at harvest was reduced by 16-cm when corn was intercropped with alfalfa compared to control treatment. In the study started in 2017, intercropped corn without PHD application had 24% lower LAI at the R1 growth stage. Whereas LAI in intercropped corn with PHD was reduced by

31 and 20% at R1 and before corn harvest, respectively, when compared to the corn only treatment, suggesting that PHD was ineffective in alleviating any potential stress on corn due to actively growing alfalfa underneath its canopy. Reduction in corn LAI in an intercropped system compared to a monocrop was also reported by Ren et al. (2016) where corn was intercropped with a legume. Corn plant height at PHD application (V8 corn growth stage) and at harvest was also reduced in 2017 in intercropped treatments (with and without PHD) compared to corn only. Alfalfa growing underneath the corn canopy may lower the red:far red ratio which can be sensed by the corn plants resulting in increased plant height and low shoot:root ratio (Rajcan et al., 2004). The reduction of plant height at early growth stage (V8) suggests nutrient and moisture competition from intercropped alfalfa, and was not resultant from the phytochrome mediated red:far red competition response. The mean corn plant height in the intercropped system at the time of PHD application was 29 cm shorter than the corn only treatment whereas, corn height in intercropped system with and without PHD was reduced by 22 and 29 cm at harvest, respectively. The differences in corn leaf area and plant height in 2017 could be an effect of lack of available soil moisture due to dry summer conditions (Table 4). As reported by Ren et al. (2016) the water consumption by alfalfa in an intercropped system is higher as compared to corn which may have resulted in competition for soil moisture between corn and alfalfa growing together.

Corn Aboveground Biomass, Harvest Index and Grain Yield

The corn harvest index (HI) in both 2016 and 2017 was not affected by alfalfa intercropping or the application of PHD and was similar to the corn only control treatment (Table 6). The mean harvest index across all treatments was 66 and 64 in 2016 and 2017, respectively. These HI values were within the range of values reported by previous studies (Khalili et al., 2013; Li et al., 2015). Aboveground biomass and grain yield in 2016 were lower

(6-14 and 11-14%, respectively) in the intercropped system when compared to corn only, but this difference was not large enough to be considered statistically significant. The application of PHD on alfalfa did not influence corn aboveground biomass or grain yield between the intercropping treatments. The aboveground biomass and grain yield across all the treatments in 2016 was 29 and 13.6 Mg ha^{-1}, respectively. In contrast to 2016, for the study established in 2017, corn aboveground biomass and grain yield were significantly different between corn only and intercropped treatments. Corn biomass was average 24% lower in both the untreated alfalfa and that treated with PHD than the corn only treatment. Similarly, corn grain yield was reduced by 24.5% when intercropped with alfalfa (with or without PHD application). Reduction in silage yield when corn was intercropped with alfalfa was reported by Osterholz et al. (2018). Similar to 2016, application of PHD did not affect the aboveground biomass or grain yield between the intercropped treatments in 2017. Similar findings were reported in the studies conducted by Osterholz et al. (2018) in Wisconsin, where application of PHD on alfalfa had little or no effect on corn plant height and grain yield when alfalfa was intercropped with silage corn. Reductions in corn biomass and grain yield in 2017 were likely the result of a drier summer and inadequate available soil moisture. Sun et al. (2019) reported that in an intercropping with corn, alfalfa was 3-5 times more competitive than corn and could dramatically increase its root growth and nutrient uptake capacity and compete with corn for available moisture and nutrient.

Soil Profile NO_3-N

Residual fall soil profile NO_3-N in the top 60 cm was significantly lower in solo alfalfa as compared to corn only or corn intercropped with alfalfa treatments in the establishment year 2016 (Table 7). However, in fall 2017, the residual soil profile NO_3-N was lower with the solo alfalfa treatment but not significantly different from the corn only or the treatments where corn was intercropped with alfalfa. In a simulation study conducted by Osterholz et al. (2019)

interseeding alfalfa with corn reduced up to 74% of total N loss through runoff water, however, in our study in both the establishment years, intercropping corn with alfalfa had no effect on residual NO_3-N and was similar to the corn only treatment. These results indicate that the solo alfalfa treatment overall had higher uptake of soil NO_3-N and acted as a N scavenger.

Alfalfa Stem Height, Growth Stage, Stem Density and Biomass

Alfalfa stem height in solo alfalfa and intercropped alfalfa treatments were not different at the time of PHD application in the establishment years of 2016 and 2017 (Table 8). The mean stem height of alfalfa across all treatments at the time of PHD application was 12 and 20 cm in 2016 and 2017, respectively. The alfalfa stem height and growth stage in fall before corn harvest was significantly higher in solo alfalfa in 2016 but was not different from intercropped alfalfa treatments in 2017. Between the intercropped alfalfa treatments with and without the application of PHD, there was no difference in plant height, growth stage, stem density and dry biomass yield at corn harvest in either 2016 or 2017 indicating there was no effect of PHD application on alfalfa survival and growth under a corn canopy. Unlike the findings of our study, Grabber (2016) successfully used PHD to increase alfalfa plant density and biomass yield when intercropped in a corn silage system. The alfalfa stem density and dry biomass yield was significantly greater in solo alfalfa compared to intercropped alfalfa treatments in both the establishment years of 2016 and 2017. Stem density in the intercropped treatments and solo alfalfa treatment in 2017 was below the recommended density of 430 stems m^{-2} (Dan and Dennis, 2007). Stem density of the alfalfa only treatment was 3 times greater than the intercropped alfalfa in 2016 whereas it was only 1.5 times greater in 2017. Similarly, dry biomass of solo alfalfa was 8 and 2 times greater compared to intercropped treatment in 2016 and 2017, respectively. The lower yield and stem density of solo alfalfa in 2017 were likely caused by the dry summer conditions (Table 3) from June -Sept. that year which may have affected alfalfa establishment and growth. Lower biomass yield and stem density of alfalfa in the intercropped system as compared to solo alfalfa indicates that alfalfa was stressed growing under the corn canopy.

Due to dry summer conditions in 2017, only three cuttings of alfalfa were harvested from the solo and intercropped alfalfa treatments from the study started in 2016 whereas only one cut was obtained from the 2017 spring seeded alfalfa. In 2018, (first production year for study started in 2017) four cuttings of alfalfa were taken for sole and intercropped treatments while spring seeded alfalfa was only harvested twice.

For the first production years in 2017 and 2018, stem height, density, growth stage and dry biomass yield did not differ between intercropped treatments with and without the application of PHD (Table 9). Significant differences in stem height, density and growth stage and biomass yield between sole and intercropped alfalfa were observed at first harvest in 2016 while in 2017 only stem height and dry matter yield in sole alfalfa was higher at first harvest. Stem height and growth stage in 2017 were lower but the stem density of spring seeded alfalfa at its first harvest (third harvest for solo and intercropped treatments) was 1.5 times that of sole and intercropped alfalfa established the year before. Spring seeded alfalfa dry matter yield at first harvest was similar to sole and intercropped treatments in 2017. However, in 2018, intercropped and sole alfalfa treatments had 3.5- and 2-times greater biomass yield at first and second cuttings of spring seeded alfalfa (Fig 1). Despite some inconsistencies at different harvest times within the same year, sole alfalfa produced the greatest total biomass yield in the first production year whereas intercropped alfalfa produced 6- and 5-times more seasonal dry biomass (total biomass from all harvests in a year) as compared to spring seeded alfalfa in 2017 and 2018, respectively. Seasonal forage yield in the first production year in our study was within the mean yield range reported by Berti et. al. (2015). Higher yield from intercropped alfalfa compared to spring seeding helps to compensate for the low production of spring seeded alfalfa and improves the overall productivity of the intercropping system.

Four cuttings of alfalfa from each treatment were harvested in the second production year of alfalfa in 2018 and 2019. There was no difference in stem height, stem density, growth stage and dry matter yield among treatments in 2018 (Table 10). The mean dry matter yield in 2018 across all the treatments was greatest for first cutting (4.5 Mg ha^{-1}) and least at the fourth cutting (0.9 Mg ha^{-1}). Mean stem density across all the treatments and harvests was 460 m^{-2}. For the second production year in 2019, there were inconsistent effects of treatments on plant height and stem density. Spring seeded alfalfa had lower plant height compared to sole and intercropped alfalfa at first harvest whereas greater stem density and lower stem height at second harvest. Dry matter yield of spring seeded alfalfa at third harvest was slightly lower compared to intercropped treatments. Low biomass yield of spring seeded alfalfa was possibly an effect of lower stem density at the time of third harvest. Despite some inconsistency among harvests, the total seasonal biomass yield for the second production year of alfalfa in 2018 and 2019 was similar across treatments (Fig 2). Mean seasonal alfalfa dry matter yield across all the treatments was 9.1 and 6.0 Mg ha^{-1} in 2018 and 2019, respectively.

The overall productivity and economic benefit of the intercropping system can be increased when yields of both the crops are combined (Sun et al., 2018; Sun et al., 2019). In our study, there was overall reduction in corn grain yield due to intercropping with alfalfa in both experimental years (Fig 3). However, the combined yield of corn aboveground biomass and total seasonal yield of first year alfalfa was either similar or greater when alfalfa was intercropped with corn compared to the conventional system where alfalfa was spring seeded following the previous year corn harvest (Fig. 3).

Alfalfa Forage Quality

Alfalfa forage samples from first production year (2017) for study stated in 2016 could not be analyzed for forage quality. Ash content and NDFD (Neutral detergent fiber digestibility) for spring seeded alfalfa in 2018 was greater at first cutting (second cutting for sole and intercropped treatment) and second cutting (Table 11). Greater fiber digestibility of spring seeded alfalfa can be explained by smaller stem height at harvest (Table 9). Shorter stems tend to have higher leaf to stem ratio and thus have less fibrous tissue. High leaf to stem ratio of spring seeded alfalfa could also explain its high protein concentration at harvest. There were no differences in ash content, protein, lignin or NDFD between sole and intercropped alfalfa in first production year.

In the second production year of alfalfa, forage quality among treatments was not different for the 2018 harvest (Table 12). However, NDFD for spring seeded alfalfa was greater at first harvest in 2019 whereas it was higher for sole alfalfa compared to intercropped alfalfa with PHD at fourth harvest.

Weed Density and Community

In fall of the establishment year, the mean weed density (weeds m^{-2}) at the time of corn harvest was greater in solo alfalfa but was not significantly different from alfalfa growing under a corn canopy. The average weed density across all treatments were 29 and 4 weeds m^{-2} in 2016 and 2017, respectively. Ample soil moisture in the 2016 growing season resulted in high weed pressure compared to dry summer conditions in 2017 (Table 4). The weed community was comprised of 94% broadleafs and 6% grasses. Major broadleaf weeds in establishment year were (41%) tall waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer], (4%) little hogweed (*Portulaca* *oleracea* L.), (26%) West Indian nightshade (*Solanum ptychanthum* Dunal.), and (11%) lambsquarters (*Chenopodium album* L.). Grassweed species mainly consisted of giant foxtail (*Setaria faberi* Herrm.), crabgrass [*Digitaria sanguinalis* (L.) Scop.] and hairy cupgrass [Eriochloa villosa (Thunb.) Kunth].

In the first production year, the overall weed density was high in spring seeded alfalfa, but it was not significantly different from solo or intercropped alfalfa. The overall weed density across treatments in spring before first harvest was 50 and 8.3 in 2017 and 2018, respectively. Weed density in fall of 2017 and 2018 was 7 and 11 weeds m^{-2}, respectively. Total weed community in the spring of first production year across 2017 and 2018 was 79% of broadleaf weeds and 21% grasses. Major broadleaf weeds in the spring were (48%) Canadian horseweed [*Conyza canadensis* (L.) Cronquist], tall water hemp (28%), dandelion (*Taraxacum sp.* L.) (13%). Other minor broadleaf weeds were field pennycress (*Thlaspi arvense* L.) lambsquarters, creeping wood sorrel (*Oxalis corniculata* L.), and speedwell (*Veronica arvensis* L). Some of the major grass weeds were crabgrass, yellow foxtail [*Setaria pumila* (Poir.) Roem. & Schult.], ryegrass (*Lolium multiflorum* Lam.), and hairy cupgrass. In the fall, before last alfalfa harvest, overall weed density was low with 7 and 11 weeds m^{-2} in 2017 and 2018, respectively. In the fall, 74% of the total weeds were broadleaf species while 26% were grasses.

In the second production year of alfalfa, mean weed density in the spring did not differ among treatments and averaged 32 and 27 weeds m^{-2} in 2018 and 2019, respectively. Broadleaf weeds were 94% of the total weed community and were mainly represented by (40%) Canadian horseweed, (29%) tall water hemp, (18%) shepherd’s purse [*Capsella bursa-pastoris* (L.) Medik.], and (5%) west Indian nightshade. Other minor broadleaf weeds were lambsquarters, dandelion, and western tansy mustard [*Descurainia pinnata* (Walter) Britton]). Grass weeds were mostly giant foxtail and crabgrass.

Conclusions

Results of our study document that corn grain yield was not affected when intercropped with alfalfa in presence of sufficient soil moisture at planting and initial growth stages. However, intercropped alfalfa reduced corn grain yield in a year with dry summer conditions. Application of PHD did not alleviate the reduction in intercropped corn grain yield or improve alfalfa survival under a corn canopy. Alfalfa intercropped with corn had lower stem density in the establishment year compared to solo established alfalfa. Total seasonal yield of intercropped alfalfa in the first production year was greater than spring seeded alfalfa, suggesting an overall increase in the total productivity of the intercropped system despite some reduction in corn grain yield. Differences in forage quality of alfalfa among treatments disappeared as the alfalfa stands grew older. Successful integration of alfalfa with corn in an intercropping system is contingent upon successful establishment of alfalfa under the corn canopy and alleviation of competition between corn and alfalfa for nutrients and soil water. Based on the findings of our experiment future research in this direction should be focused on screening drought tolerant corn hybrids with vigorous root system. Using early maturing corn hybrid coupled with management practices such as higher rates of N fertilizer may improve corn yield and the chances of success for this intercropping system. Efforts should also be made towards improving the alfalfa stand density in the establishment year by investigating different rates of growth regulator and effectively managing weeds and pest.

Acknowledgments

This research was supported by a grant funded by USDA-National Institute of Food and Agriculture-Coordinated Agricultural Program (Award number: 2016-69004-24784). We are

grateful for field and technical support provided Agricultural and engineering farm research crew, hourly undergraduates, and Assistant scientist Roger Hintz.

References

Abendroth, L.J, R.W. Elmore, M.J. Boyer, and S.K. Marlay. 2011. Corn growth and development. Publ. PMR-1009. Iowa State Univ. Ext. https://store.extension.iastate.edu/Product/Corn-Growth-and-Development (accessed 28 Feb. 2020).

Herzmann, D. 2020. Iowa environmental mesonet. Iowa State Univ., Ames, IA. https://mesonet.agron.iastate.edu/climodat/index.phtml?network=IACLIMATE&station=IA0200&report=17 (accessed 20 February 2020).

Anil, L., J. Park, R.H. Phipps, and F.A. Miller. 1998. Temperate intercropping of cereals for forage: a review of the potential for growth and utilization with particular reference to the UK. Grass Forage Sci. 53(4):301-317.

Berti, M.T. 2015. Alfalfa performance test. North Dakota State Univ. Available at https://www.ag.ndsu.edu/plantsciences/research/forages/alfalfa (verified 25 January 2018).

Cataldo, B.A., M. Haroon, L.E. Schrader, and V.L. Youngs. 1975. Rapid colorimetric determination of nitrate in plant tissue by nitrate in plant tissue by nitration of salicylic acid. Commun. Soil Sci. Plant Anal. 6:71-80.

Dan, U, and C. Dennis. 2007. Using stem count as a decision aid in turning over alfalfa stands. Forage and Grazinglands. 5:0-0.

Grabber, J. H. 2016. Prohexadione–Calcium improves stand density and yield of alfalfa interseeded into silage corn. Agron. J. 108:726-735.

Hatfield, J.L., L.D. McMullen, and C.S. Jones. 2009. Nitrate-nitrogen patterns in the Raccoon River Basin related to agricultural practices. J. Soil Water Cons. 64:190-199.

Kalu, B.A. and G.W. Fick. 1983. Morphological stage of development as a predictor of alfalfa herbage quality 1. Crop Sci. 23(6):1167-1172.

Khalili, M., M.R. Naghavi, A.P. Aboughadareh, and H.N. Rad. 2013. Effects of drought stress on yield and yield components in maize cultivars (Zea mays L.). Int. J. Agron. Plant Prod. 4:809-812.

Li, J., R. Z. Xie, K. R. Wang, B. Ming, Y. Q. Guo, G. Q. Zhang, and S. K. Li. 2015. Variations in maize dry matter, harvest index, and grain yield with plant density. Agron. J. 107:829-834.

Mallarino, A.P., J.E. Sawyer, and S.K. Barnhart. 2013. A general guide for crop nutrient and limestone recommendations in Iowa. PM-1688. Iowa State Univ. Ext. and Outreach, Ames, IA.

Matusso J. M. M., J. N. Mugwe, and M. Mucheru-Muna. 2014. Effect of different maize (Zea mays L.)-soybean (Glycine max (L.) Merrill) intercropping patterns on yields, light interception and leaf area index in Embu west and Tigania east sub counties. Abstract. *Academic Res. Jour. of Agri. Sci and Res.* 2(2): 6-21.

Mikic, A., B. Cupina, D. Rubiales, V. Mihailovic, L. Sarunaitek, J. Fustec, et al. 2015. Models, developments, and perspectives of mutual legume intercropping. In: D. L. Sparks, editor Advances in Agronomy. Elsevier Academic Press Inc, San Diego. 130:337-419.

Olmstead, J., and E. Brummer. 2008. Benefits and barriers to perennial forage crops in Iowa corn and soybean rotations. Ren. Agri. and Food Sys 23(2):97-107.

Osterholz, W.R., M.J. Renz, J.G. Lauer, and J.H. Grabber. 2018. Prohexadione-calcium rate and timing effects on alfalfa interseeded into silage corn. Agron. J. 110(1):85-94.

Pendleton, J.W., J.A. Jackobs, F.W. Slife, and H.P. Bateman. 1957. Establishing legumes in corn. Agron. J. 49(1):44-48.

Rademacher, W. 2000. Growth retardants: Effects on gibberellin biosynthesis and other metabolic pathways. Annu. Rev. Plant Physiol. Plant Mol. Biol. 51:501–531. doi:10.1146/annurev.arplant.51.1.501

Rajcan, I., K. Chandler, and C. Swanton. 2004. Red-far-red ratio of reflected light: A hypothesis of why early-season weed control is important in corn. Weed Sci. 52(5):774-778.

Ren, Y., J. Liu, Z. Wang, and S. Zhang. 2016. Planting density and sowing proportions of maize–soybean intercrops affected competitive interactions and water-use efficiencies on the Loess Plateau, China. Eur J Agron. 72:70-79.

Rethwisch, M.D., R. Perez, B.J. Griffin, A. Bradley, and M. Reay. 2003. Alfalfa yield and quality responses to applications of three types of plant growth regulators. Forage and Grain Report. https://repository.arizona.edu/bitstream/handle/10150/205397/az13221b-2003.pdf?sequence=1&isAllowed=y (accessed 20 Feb. 2016).

Seran, T.H. and I. Brintha. 2010. Review on maize based intercropping. J. of Agron. 9(3):135-145.

Stephens, R.J. 1982. Effects of weed infestation on crop yield and quality. In: Theory and practice of weed control. Palgrave, London. https://doi.org/10.1007/978-1-349-86066-1_1

Sun, T., Z. Li, Q. Wu, T. Sheng, and M. Du. 2018. Effects of alfalfa intercropping on crop yield, water use efficiency, and overall economic benefit in the Corn Belt of Northeast China. Field Crops Res. 216:109-119.

Sun, B., Y. Gao, H. Yang, W. Zhang, and Z. Li. 2019. Performance of alfalfa rather than maize stimulates system phosphorus uptake and overyielding of maize/alfalfa intercropping via changes in soil water balance and root morphology and distribution in a light chernozemic soil. Plant Soil. 439(1-2):145-161.

Wu, S., P. Wu, H. Feng, and G.P. Merkley. 2011. Effects of alfalfa coverage on runoff, erosion and hydraulic characteristics of overland flow on loess slope plots. Frontiers of Env. Sci. & Eng. in China. 5(1):76-83.

Yost, M.A., M.P. Russelle, and J.A. Coulter. 2014. Field-specific fertilizer nitrogen requirements for first-year corn following alfalfa. Agron. J. 106:645-658.

Yun, F., J. Wang, F.Q. Wu, W.J. Yin, X. Gao, and W.P. Cao. 2011. Soil water in a corn-alfalfa intercropping system on slope land [J]. Agri. Res. in the Arid Areas. 1.

Zhang, F.L. and L. Li. 2003. Using competitive and facilitative interactions in intercropping systems enhances crop productivity and nutrient-use efficiency. Plant Soil. 248(1-2):305-312.

Zhang, G., Z. Yang, and S. Dong. 2011. Interspecific competitiveness affects the total biomass yield in an alfalfa and corn intercropping system. Field Crops Res. 124(1):66-7

Zhang, G., Ch. Zhang, Z. Yang, and S. Dong. 2013. Root distribution and N acquisition in an alfalfa and corn intercropping system. J. Agric. Sci. 5:128-141.

Figures and Tables

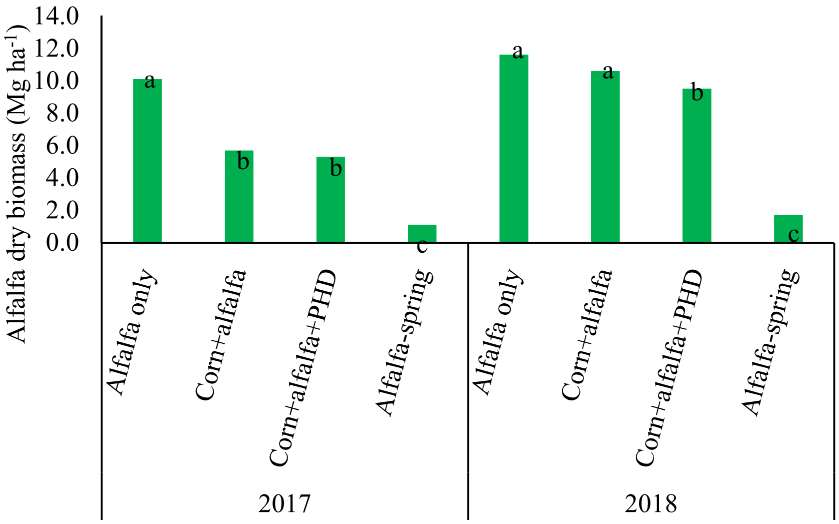

Fig. 1. Seasonal alfalfa dry forage yield for first year of production in 2017 and 2018 at Ames, IA.

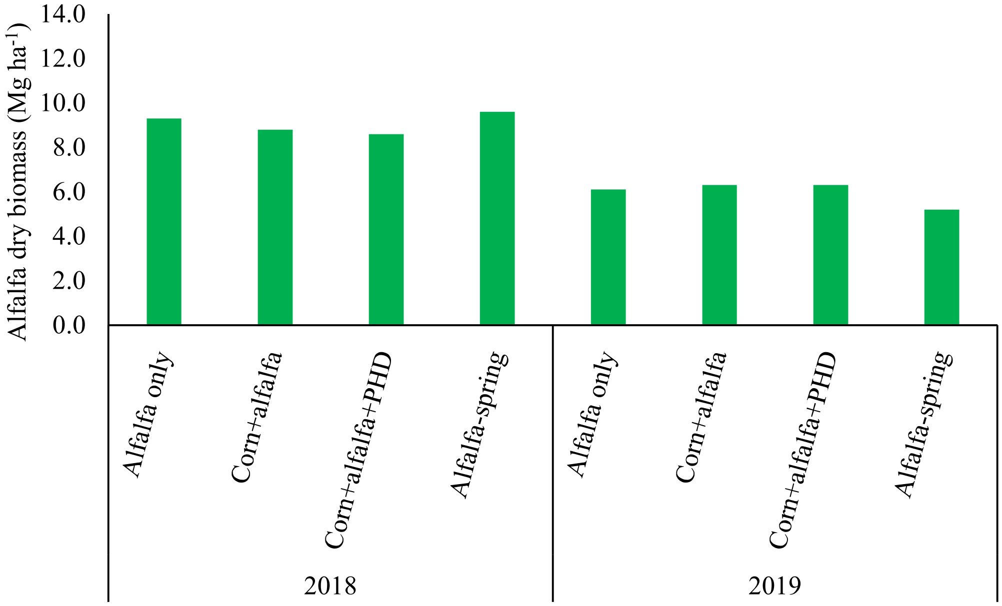

Fig. 2. Seasonal alfalfa dry forage yield for second year of production in 2018 and 2019 at Ames, IA.

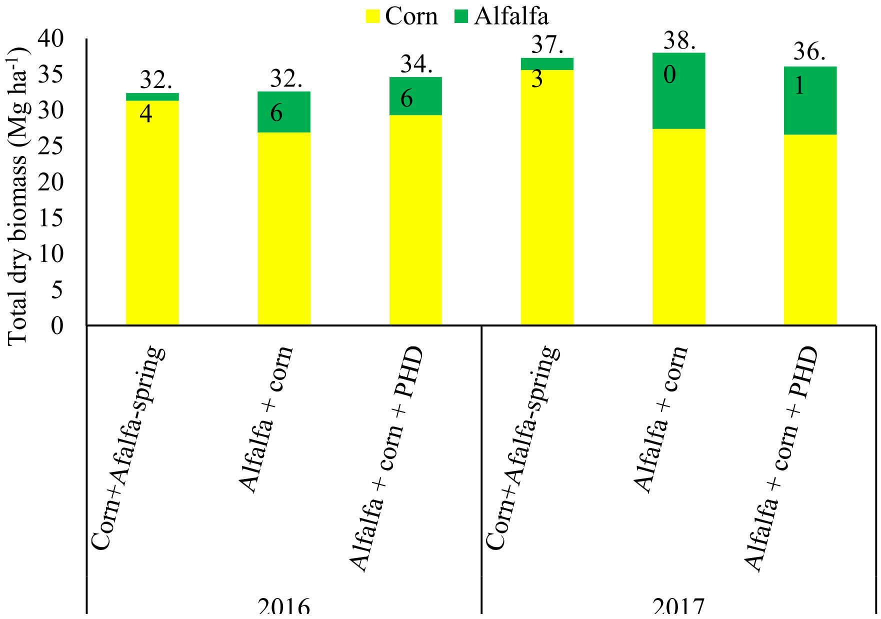

Fig. 3. Total dry matter yield of aboveground corn biomass plus first year alfalfa in studies started in 2016 and 2017 at Ames, IA.

Table 1. Baseline soil test values (0-15 cm) and soil information for study site at Boone, IA in 2016 and 2017.

Site	STP ‡	STK ‡	SOM§	pH
Boone 2016	9 (L)	80 (VL)	4.3	6.6
Boone 2017	2 (VL)	80 (VL)	4.5	6.5

† L, loam; Scl, silty clay loam.

‡ STP, soil test P; STK, soil test K. Letters indicate Olsen for P and Mehlich-3 for K soil test interpretation category for L, low; VL, very low (Mallarino et al., 2013).

§ SOM, soil organic matter.

Table 2. Corn and alfalfa seeding and proxehadione (PHD) application dates for experiment conducted from 2016-2018 at Boone, IA.

	Year		
Field activity	2016	2017	2018
Corn seeding	17 May 2016	16 May 2017	-
Alfalfa seeding	17 May 2016	16 May 2017	-
PHD application	24 June 2016	5 July 2017	-
Spring alfalfa seeding	-	16 May 2017	11 May 2018

Table 3. Harvest dates of alfalfa and corn for study conducted from 2016-2019 at Boone, IA.

	---Alfalfa---						Corn
Year	Harvest 1	Harvest 2	Harvest 3	Harvest 4	Harvest 1[†]	Harvest 2[†]	
Study started in 2016							
2016	10 Nov.	-	-	-	-	-	13 Nov.
2017[‡]	31 May	20 July	13 Sept.	-	-	13 Sept.	
2018	1 June	12 July	22 Aug.	26 Oct.			
Study started in 2017							
2017	23 Nov.	-	-	-	-	-	30 Nov.
2018	1 June	12 July	22 Aug.	26 Oct.	12 July	8 Sept.	
2019	4 June	10 July	8 Sept.	3 Nov.			

† Harvest dates of spring seeded alfalfa

Table 4. Monthly mean air temperature (°C) and monthly total rain fall (cm) in 2016, 2017, 2018, 2019 and long-term mean at Boone, IA.

Month	Year								LT[†]	
	2016		2017		2018		2019			
	T[‡]	RF[§]	T	RF	T[‡]	RF[§]	T	RF	T	RF
Jan.	-6.5	1.5	-4.0	4.7	-6.8	3.3	-6.8	1.4	-6.1	1.55
Feb.	-1.6	1.7	2.6	3.0	-5.6	2.9	-9.1	4.3	-4.2	2.21
Mar.	7.1	3.8	3.7	7.9	2.2	6.3	0.1	3.8	3.3	4.98
Apr.	11.1	10.4	11.4	7.8	5.4	3.2	11.2	4.9	10.4	10.04
May	16.3	10.9	16.3	15.6	20.6	10.1	14.9	21.1	16.5	12.29
June	23.7	2.5	22.8	4.4	23.5	28.2	21.7	10.1	21.6	12.78
July	23.4	14.9	24.4	2.5	23.5	10.7	24.3	11.7	23.3	11.96
Aug.	22.6	20.9	20.8	8.5	22.8	21.4	21.5	3.3	22.1	12.57
Sep.	20.6	20.1	20.4	4.6	19.8	17.1	21.3	11.6	18.2	8.27
Oct.	14.6	1.5	12.7	15.4	10.2	12.3	9.5	13.3	11.4	6.05
Nov.	8.0	4.4	3.6	0.7	-0.2	4.1	0.5	3.4	3.2	4.76
Dec.	-4.1	3.0	-3.8	0.4	-1.4	6.7	-1.6	2.6	-3.9	2.97

[†]LT = Long term, [‡]T= mean air temperature; and [§]RF= total monthly rain fall.

Table 5. Corn leaf area index (LAI), plant height (Ht) and plant population (Pop) in response to alfalfa interseeding treatments for experiments started in 2016 and 2017 at Boone, IA.

	LAI			Ht		Pop	
	PHD	R1	Harvest	PHD	Harvest	PHD	Harvest
Treatment[†]				-------cm-------		-------ha^{-1}-------	
			2016				
Check	1.5	4.3	3.2	92.3	226	80380	75655
Corn+alfalfa	1.1	4.3	2.9	93.6	210	75459	73810
Corn+alfalfa+PHD	1.4	4.2	3.3	89.5	215	86942	78115
SE	0.11 [‡]	0.12	0.17	3.94	4.97	4366	2939
		Significant $P > F$					
Check vs. corn+alfalfa	*	NS	NS	NS	*	NS	NS
Check vs. corn+alfalfa+PHD	NS	NS	NS	NS	NS	NS	NS
Corn+alfalfa vs. corn+alfalfa+PHD	NS	NS	NS	NS	NS	NS	NS
			2017				
Check	4.0	4.2	3.0	170	233	73425	68428
Corn+Alfalfa	3.1	3.2	2.6	141	211	70350	66890
Corn+Alfalfa+PHD	3.1	2.9	2.4	142	204	68812	68428
SE	0.34	0.25	0.16	6.05	5.35	3768	3626
		Significant $P > F$					
Check vs. corn+alfalfa	NS	*	NS	**	*	NS	NS
Check vs. corn+alfalfa+PHD	NS	**	*	**	**	NS	NS
Corn+alfalfa vs. corn+alfalfa+PHD	NS	NS	NS	NS	NS	NS	NS

*, **, *** Significant at $P < 0.05$, 0.01, and 0.001, respectively.

[†] Treatments: check, corn planted alone; alfalfa+corn, corn intercropped with alfalfa; corn+alfalfa+PHD, corn intercropped with alfalfa with an application of prohexadione.

[‡] Indicates weighted SE for all variables.

Table 6. Corn aboveground biomass, grain yield at 15.5% moisture and HI in response to alfalfa interseeding treatments for experiments started in 2016 and 2017 at Boone, IA.

	2016			2017		
	Biomass	Grain	HI	Biomass	Grain	HI
Treatment[†]	-----Mg ha^{-1}-----			----Mg ha^{-1}----		
Check	31.3	14.9	65	35.6	14.2	66
Corn+alfalfa	26.9	13.2	67	27.4	10.5	63
Corn+alfalfa+PHD	29.3	12.8	66	26.6	11.0	62
SE	2.8[‡]	1.1	0.9	2.0	0.8	1.4
			Significant $P > F$			
Check vs. corn+alfalfa	NS	NS	NS	*	**	NS
Check vs. corn+alfalfa+PHD	NS	NS	NS	*	**	NS
Corn+alfalfa vs. corn+alfalfa+PHD	NS	NS	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

[†] Treatments: check, corn planted alone; alfalfa+corn, corn intercropped with alfalfa; corn+alfalfa+PHD, corn intercropped with alfalfa with an application of prohexadione.

[‡] Indicates weighted SE for all variables.

Table 7. Residual soil NO3-N in late fall for establishment year of alfalfa in 2016 and 2017.

	Fall 2016	Fall 2017
	NO_3-N (0-60 cm)	
Treatment[†]	------------Kg ha^{-1}------------	
Alfalfa only	35b‡	41
Corn only	59a	52
Corn+alfalfa	60a	60
P>F	*	NS

*: Significant at $P < 0.05$

[†] Treatments: alfalfa only, solo seeded alfalfa; corn only, solo planted corn; corn+alfalfa, corn intercropped with alfalfa.

‡ Means with same letter in the column are not different from each other.

Table 8. Alfalfa plant height at prohexadione application (Ht1) and at harvest (Ht2); alfalfa growth stage (Stage), stem density (stem), and dry biomass yield (DM) in establishment year of alfalfa in 2016 and 2017. Alfalfa growth stage was measured as per Kalu and Fick (1983).

			2016		
	Ht1	Ht2	Stage	Stem	DM
Treatment[†]	------cm------			m^{-2}	Mg ha^{-1}
Alfalfa only	11.2	44.9a‡	2a	590a	1.6a
Corn+alfalfa	12.2	13.7b	0b	173b	0.2b
Corn+alfalfa+PHD	11.6	13.8b	1b	203b	0.2b
P>F	NS	***	**	***	***
			2017		
Alfalfa only	19.4	30.7	2	292a	1.1a
Corn+alfalfa	20.4	30.4	2	214ab	0.7b
Corn+alfalfa+PHD	20.6	27.3	1	160b	0.5b
P>F	NS	NS	NS	*	**

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

[†] Treatments: alfalfa only, solo seeded alfalfa; alfalfa+corn, corn intercropped with alfalfa; corn+alfalfa+PHD, corn intercropped with alfalfa with an application of prohexadione.

‡ Means with same letter in the column are not different from each other.

Table 9. Alfalfa stem height (Ht), growth stage (Stage), stem density (Stem) at each harvest and total seasonal dry biomass (DM) for first production year of alfalfa in 2017 and 2018. Alfalfa growth stage was measured as per Kalu and Fick (1983).

	Harvest1				Harvest2				Harvest3				Harvest4			
	Ht	Stage	Stem	DM	Ht	Stage	Stem	DM	Ht	Stage	Stem	DM	Ht	Stage	Stem	DM
Treatment†	cm		m^{-2}	Mg ha^{-1}	cm		m^{-2}	Mg ha^{-1}	cm		m^{-2}	Mg ha^{-1}	cm		m^{-2}	Mg ha^{-1}
2017																
T1	70a‡	4a	453a	5.4a	49a	7	528	2.6	65a	6a	368b	2.1	NA	NA	NA	NA
T3	41b	3b	265b	2.0b	39a	7	474	2.0	58a	6a	355b	1.7	NA	NA	NA	NA
T4	45b	3b	250b	1.6b	40b	7	409	1.8	62a	6a	321b	1.9	NA	NA	NA	NA
T5	NA§	NA	NA	NA	NA	NA	NA	NA	46b	4b	527a	1.1	NA	NA	NA	NA
P>F	**	*	*	***	**	NS	NS	NS	**	***	**	NS				
2018																
T1	77a	6	837	6.2a	51a	6a	538	2.5a	59	5a	457	2.0a	36	2	459	1.0
T3	66b	5	706	5.0ab	48a	6a	585	2.5a	56	5a	459	2.1a	37	2	522	1.0
T4	62b	5	711	4.3b	47a	6a	587	2.3a	58	5a	499	2.0a	34	2	557	0.9
T5	NA	NA	NA	NA	21b	1b	715	0.7b	49	4b	573	1.0b	NA	2	NA	NA
P>F	**	NS	NS	*	***	***	NS	***	NS	**	NS	*	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

†Treatments: T1, alfalfa only; T3 is corn intercropped with alfalfa; T4, corn intercropped with alfalfa with an application of prohexadione; T5, spring seeded alfalfa

‡ Means with same letter in the column are not different from each other.

§Alfalfa not harvested

Table 10. Alfalfa stem height (Ht), growth stage (Stage), stem density (Stem) at each harvest and total seasonal dry biomass for second production year of alfalfa in 2018 and 2019. Alfalfa growth stage was measured as per Kalu and Fick (1983).

	Harvest1				Harvest2				Harvest3				Harvest4			
	Ht	Stage	Stem	DM	Ht	Stage	Stem	DM	Ht	Stage	Stem	DM	Ht	Stage	Stem	DM
Treatment[†]	cm		m^{-2}	Mg ha^{-1}	cm		m^{-2}	Mg ha^{-1}	cm		m^{-2}	Mg ha^{-1}	cm		m^{-2}	Mg ha^{-1}
2018																
T1	73	5	502	5.1	48	7	493	1.7	47	6	468	1.7	30	2	462	0.8
T3	70	5	422	4.2	45	6	504	1.8	51	6	451	1.9	34	2	465	0.9
T4	69	5	448	3.8	48	6	534	2.0	47	5	440	1.8	33	2	437	0.9
T5	68	6	378	5.0	43	6	552	2.2	47	5	379	1.6	35	2	442	1.0
$P>F$	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
2019																
T1	60a[‡]	5	397	2.7	41a	6	434b	1.7	39	2	331b	0.8bc	35	2	353	0.9
T3	61a	5	443	2.9	41a	6	454b	1.7	41	2	363ab	0.9ab	37	2	357	0.9
T4	58a	4	477	2.5	40a	6	510ab	1.8	41	2	398a	1.0a	38	3	404	1.1
T5	47b	4	497	2	36b	6	574a	1.7	41	2	305b	0.7c	35	2	403	0.9
$P>F$	*	NS	NS	NS	*	NS	*	NS	NS	NS	*	**	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

[†] Treatments: T1, alfalfa only; T3 is corn intercropped with alfalfa; T4, corn intercropped with alfalfa with an application of prohexadione; T5, spring seeded alfalfa

‡ Means with same letter in the column are not different from each other.

Table 11. Alfalfa forage quality in 2018; first production year for the experiment started in 2017.

	2018															
	Harvest1				Harvest2				Harvest3				Harvest4			
	Ash	Protein	LN	NDFD	Ash	Protein	LN	NDFD	Ash	Protein	LN	NDFD	Ash	Protein	LN	NDFD
Treatment†	----------g kg^{-1}----------															
T1	97	247	84	421	69b	190	70ab	473b	87b	190b	93	395b	79	224	67	394
T3	88	250	82	430	60c	190	62bc	489b	90ab	200b	92	403b	79	226	65	399
T4	87	254	81	424	60c	188	58c	503b	85b	189b	90	392b	78	218	68	388
T5	NA§	NA	NA	NA	84a	199	78a	380a	98a	254a	89	455a	NA	NA	NA	NA
P>F	NS	NS	NS	NS	***	NS	*	***	*	***	NS	***	NS	NS	NS	NS

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

LN: Lignin, NDFD: Neutral detergent fiber digestibility.

†Treatments: T1, alfalfa only; T3 is corn intercropped with alfalfa; T4, corn intercropped with alfalfa with an application of prohexadione; T5, spring seeded alfalfa

‡ Means with same letter in the column are not different from each other.

§Alfalfa not harvested

Table 12. Alfalfa forage quality in 2018 and 2019, second production year for the experiment started in 2016 and 2017, respectively.

	2018															
	Harvest1				Harvest2				Harvest3				Harvest4			
	Ash	Protein	LN	NDFD	Ash	Protein	LN	NDFD	Ash	Protein	LN	NDFD	Ash	Protein	LN	NDFD
Treatment[†]	-------------g kg^{-1}-------------				-------------g kg^{-1}-------------				-------------g kg^{-1}-------------				-------------g kg^{-1}-------------			
T1	64	191	69	473	83	186	93	392	85	248	79	419	80	227	67	387
T3	64	191	67	481	84	192	91	396	90	242	81	411	80	223	64	395
T4	63	195	66	481	85	190	89	395	87	243	80	410	79	224	65	396
T5	64	204	62	484	89	207	87	406	90	249	80	409	80	227	63	393
P>F	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	2019															
T1	78	188	78	419b‡	69	197	67	446	79	249	56	435	79	244	56	446a
T3	82	192	76	421b	65	193	67	441	79	246	57	431	80	246	57	434ab
T4	80	187	76	419b	66	192	65	443	79	243	58	431	79	241	59	425b
T5	76	197	69	441a	65	201	67	441	80	243	57	435	79	244	56	437ab
P>F	NS	NS	NS	**	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*

*, **, ***: Significant at $P < 0.05$, 0.01, and 0.001, respectively.

LN: Lignin, NDFD: Neutral detergent fiber digestibility.

[†] Treatments: T1, alfalfa only; T3 is corn intercropped with alfalfa; T4, corn intercropped with alfalfa with an application of prohexadione; T5, spring seeded alfalfa.

‡ Means with same letter in the column are not different from each other.

CHAPTER 5. GENERAL CONCLUSION

Corn and soybean grown in short rotations (corn-soybean, corn-corn-soybean) are the most popular cropping systems in the upper Midwest of United States. Although monoculture corn and soybean or their rotation are highly productive, there are environmental problems associated with them, and questions persist as to their long-term sustainability. In view of futu challenges, there is need to diversify the existing cropping systems by adopting farming practi that not only maintain high yields but also incorporate multiple environmental benefits from agroecosystems. Due to the below-freezing winter temperatures in the Midwest, there is no cr grown from late fall to early spring. The absence of any vegetation and ground cover during th winter results in loss of soil and nutrients from erosion and leaching. Adoption of cover crops recommended to address this issue, however, issues such as choice of cover crop, problems w successful establishment of cover crops and costs associated with establishing cover crops discourages farmers from adopting them despite several proven environmental benefits. In thi research project, novel management practices were investigated to intensify and diversify the dominant corn and soybean cropping system through integration of annual oilseed cover crop and a perennial forage. The overall objective of this dissertation research was to assess the establishment and management of pennycress and camelina as oilseed cover crops in corn an soybean and their impact on row crop yield. Pennycress, winter camelina, and cereal rye were interseeded in corn and soybean in the fall and the following spring soybean was relay plante into growing pennycress and camelina after rye was terminated. In a separate study, alfalfa wa intercropped with corn with the objective to determine the overall productivity of corn-alfalfa intercropping system compared to the conventional system where alfalfa was seeded in spring following the previous year corn.

In the second chapter that focuses on integrating and managing oilseed cover crops in corn and soybean, we determined that interseeding pennycress, camelina, and cereal rye as cover crops in corn and soybean from mid-August to late September did not affect row crop yield. Fall survival of pennycress and camelina was affected by interseeding date and timing of rainfall. Oilseed cover crop survival was maximized when interseeded at R5 and R6 into corn and R7 and R8 into soybean.

In the third chapter, interseeded pennycress and camelina yield and their influence on row crops was evaluated. Pennycress and camelina harvested for seed had greater yield when interseeded at later seeding dates the previous fall. Both pennycress and camelina interseeded into the previous year corn reduced yield of the relay cropped soybean. Total oilseed yield of the relay system was greater with pennycress compared to the no cover crop control suggesting there is potential for adopting pennycress as a cash cover crop.

In the fourth chapter, management, productivity and weed community dynamics were studied in a corn-alfalfa intercropping system in Iowa. We determined that alfalfa when interseeded with corn in a dry year reduced corn grain yield by 23-26%. Alfalfa stem density when interseeded with corn was reduced by 36-38%. However, alfalfa forage yield in the first production year was 5-6 times greater than spring seeded alfalfa, increasing overall productivity of the intercropping system. Results of this study indicate that corn-alfalfa intercropping is very promising for increasing overall productivity. Further research is recommended to investigate corn and alfalfa traits such as drought tolerance, shade tolerance, pesticide management and earlier maturing corn varieties.