RELAY-SOWING SOYBEAN INTO ESTABLISHED WINTER ANNUAL COVER CROPS

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

Cover crop acreage continues to increase as soil, grazing, and ecosystem benefits become better known. The profit aspect of sustainability could be improved by producing intersown cover crops with an added commodity value. Objectives of this research were to determine if field pennycress, winter camelina, and winter rye could act as effective, feasible, intersown cover crops in soybean-soybean-corn, and, corn-soybean-corn crop sequences. Three sowing dates of each crop were established the previous fall, and soybean, relay-sown the following spring at Prosper and Casselton, ND. Experimental design was a 10 treatment, four replicate, randomized complete block with a 3×3 factorial arrangement, and one non-treated check (NTC) within each replicate. In both crop sequences, treatments containing field pennycress and winter camelina had either similar, or reduced soybean seed yield in relation to the (NTC). Additional yield obtained from field pennycress and/or winter camelina seed did not render this cropping system economically feasible.

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INTRODUCTION AND JUSTIFICATION

Sustainability, land use efficiency, and soil health are aspects of crop production that are paramount to today's producers. The use of cover crops in North Dakota and surrounding Midwestern states has dramatically increased in recent years due to of their positive impact on cropping systems. Traditionally, cover crops sown following the primary crop have been annuals or winter-annuals that are grazed, harvested for forage, or terminated at the time of sowing in the subsequent growing season. A new aspect of this management practice now receiving attention is the production of winter annual cover crops that have commodity value when fall intersown into soybean, *Glycine max* (L.) Merr., or corn (*Zea mays* L.) and harvested for seed in the subsequent growing season. Then, soybean is relay-sown into the established winter annuals with each crop harvested at its respective maturity. Gallagher (2009) defines intercropping as two crops being grown at the same time for either a portion or the entirety of their growth cycle within a period of 12 months; and relay cropping as a type of intercropping where two crops are grown together during the same growing season for a portion of their growth cycles.

Due to the intensity of this cropping system and the fact that it is not widely, if at all utilized in this region currently, it is imperative that producers be presented with research that illustrates what they would experience if they chose to integrate this into their operation. If practical, this could allow producers to reap the benefits of having a cover crop on their land while simultaneously increasing their economic return per acre by harvesting three crops in two growing seasons; in addition to improving soil health and maximizing land use efficiency.

LITERATURE REVIEW

Corn

Corn (*Zea mays* L.) was first domesticated in the southern region of Mexico between 5000 and 8000 B.C. (Goodman, 1988). A member of the grass (Poaceae) family, corn is a major commodity in the United States with 36.1 million-ha sown in 2018, with 1.4 million-ha sown in North Dakota (USDA, 2018). Corn requires a minimum temperature of 10°C for growth (NDSU, 2017). This base temperature has an important role in the calculation of accumulated growing degree days, a common method for determining crop development. Of the total 2018 corn acreage in the United States, 92% was sown using hybrids that had some form of biotechnology (USDA, 2018). The ethanol industry consumes a substantial amount of the annual corn production with approximately 37.6% of the total metric tons produced in 2017 going towards ethanol production (USDA, 2018).

Soybean

Soybean, *Glycine max* (L.) Merr., is classified as a dicotyledonous plant and member of the legume (Fabaceae) family and exhibits an active hypocotyl or epigeal type of emergence. With this type of emergence soybean is vulnerable to frost in the spring since the terminal growing point of the plant is brought above ground along with any axillary buds (Kandel, 2010). This requires producers to be diligent in choosing the proper soybean sowing date. In 2018, 36.2 million ha of soybean were sown in the United States, with 2.7 million-ha sown in North Dakota (USDA, 2018). Of the total acreage sown in 2018, 94% had some form of biotechnology trait.

Crop rotation (corn-soybean)

Crop rotations in production agriculture are an ancient management practice known to enhance sustainability (White, 1970). Implementing crop rotations within a production system provides producers the opportunity to control weeds with herbicides that have different chemical modes of action. This enhances weed control and slows the development of herbicide resistant weeds (Doucet et al., 1999). The presence of host specific pests and pathogens is also reduced through crop rotation (Ball et al., 2005). Additionally, from a financial standpoint, utilizing a crop rotation can aid producers in obtaining maximum economic return per acre by mitigating risk through diversification and increasing yield and quality to ensure high crop value at the time of harvest (Pierce and Rice, 1988).

Across the Midwestern region of the United States, crop rotations involving corn and soybean are prominent (Porter et al., 1997). By having these crops in rotation, the yields experienced at harvest have been recorded to be 15% to 17% higher compared with if they were grown in continuous monoculture (Crookston et al., 1991). This statistic holds true to the term "rotation effect", referring to the yield increases observed with crops in rotation (Pierce and Rice, 1988). Improvements in seedling root vigor and development are also observed from these crops being in rotation. Both of these factors allow the plants access to additional nutrients and water found deeper in the profile (Nickel et al., 1995). It is also thought that corn and soybean in rotation maximize the amount of beneficial arbuscular mycorrhizal fungi (AMF) present in the soil which aids their root systems in taking up immobile nutrients, such as P, Cu, and Zn (Johnson et al., 1992).

Intercropping systems

Intercropping systems that span two growing seasons provide increased land use efficiency and diversification at northern latitudes where seasonal growing degree day accumulation is limited (Berti et al., 2015). In an intercropping system, a winter-annual crop is intersown into an established annual crop in the first season. Then, a third annual crop is relay-sown into the winter-annual crop in the second season prior to bolting (stem elongation) of the winter-annual. Two crops (annual and winter-annual) are sown in the first growing season and one crop (annual) is harvested for seed/grain. In the second season, one crop (annual) is sown, and two crops are harvested (winter-annual and annual) for seed/grain. This provides the producer with three cash crops in just two growing seasons (Gesch et al., 2014).

In addition to being harvested as a cash commodity, the second crop (winter-annual) also acts as a cover crop. Ecosystem benefits beyond the additional commodity income are observed from these cropping systems. These benefits include added soil organic matter, erosion control, and improved soil structure and productivity (Hartwig and Ammon, 2002). Cover crops also have the potential to act as a resource for pollinators early in the growing season. This is because winter-annual oilseeds such as winter camelina, *Camelina sativa* (L.) Crantz., and field pennycress (*Thlaspi arvense* L.) typically flower during the time that native insects are coming out of hibernation and honey bee (*Apis mellifera* L.) hives are being brought back to northern latitudes for honey production during the summer months (Eberle et al., 2015).

When determining if intercropping systems can be integrated into regional crop rotations, two factors that must be evaluated are; average accumulated growing degree days and available soil water (Berti et al., 2015). If either of these factors are not able to support the production of three crops in two growing seasons, it is not economical to adapt a cash intercropping system. In intercropping systems, oilseed crops, and in particular winter camelina, are thought to be low water users when compared with primary crops of corn and soybean; and well suited to be intersown cover crops for the region of eastern North Dakota and northwestern Minnesota (Gesch and Johnson, 2015).

Results from studies conducted by Gesch and Johnson (2015) in 2010 and 2011, both with normal-to-above normal rainfall, determined that in winter camelina and soybean intercropping systems additional water usage from April through soybean harvest (prior water usage of winter camelina from its fall sowing up until April was not recorded) in each year was only 0.25-and 0.50-cm greater, respectively, than what was experienced in monocropped soybean. In addition, not only did camelina require substantially less water than soybean, but the authors determined peak water usage of camelina tends to occur early in the growing season when primary crops have low water demand, and rainfall is generally favorable. Specifically in this study winter camelina had the greatest water demand from mid-May through early-June, whereas soybean did not have a substantial water demand until the months of July and August; thus allowing time between these periods for soil water recharge.

In growing seasons where rainfall is below normal, however, additional water use of winter camelina can be substantial enough to incur yield loss on the primary crop. In experiments conducted during 2018 by Cabello-Leiva et al. (2018) sugar beet (*Beta vulgaris* L.), and corn, sown into an established cover crop of winter camelina experienced yield loss due to the additional water demand from winter camelina. Although peak water demand in winter camelina does not occur at the same time as peak water demand in sugar beet or corn, the early season water demand of the shallow rooted winter camelina decreases soil water in the uppermost portion of the soil profile, if seasonal rainfall is below normal (Gesch and Johnson 2015). This reduction in available soil water has adverse effects on stand establishment, and ultimately yield of the relay-sown primary crop.

Yields of intercropping systems are competitive with those of monocrop systems. Though there is typically a yield deficit in the primary crop, seed and oil yield from the winter-annual usually more than compensates for this loss (Gesch et al., 2014). In a study conducted from 2009-2011 by Gesch et al. (2014), overall yield of two different relay and two different double-cropping treatments of winter camelina and soybean were analyzed and compared against the yield of a monocropped soybean control treatment. When averaged across years monocropped soybean yield was 3703 kg ha^{-1} and soybean yield in the two relay-cropping treatments (soybean sown "before or at camelina bolting") and (soybean sown "before or at camelina bolting and treated with glyphosate 7 to 10 d earlier than straight camelina harvest") was 2474 and 2792 kg ha^{-1}, respectively. Though soybean yield in these treatments was less than what was obtained in the monocropped soybean control, an additional 1100 to 1300 kg ha^{-1} winter camelina seed yield was obtained from these treatments as well. Thus providing similar, if not greater overall seed and oil yield, and gross income; based on the author's assumption that winter camelina holds a commodity value similar to that of canola (Gesch et al., 2014). Intercropping was also deemed to provide soybean yields 33 to 70% higher than both of the double-cropping treatments ("double-cropping of soybean following camelina harvest") and ("double-cropping of soybean after swathing camelina"), with the intercropping treatment of soybean sown "before or at camelina bolting" being the most economical out of the four tested (Gesch et al., 2014).

Field pennycress

Field pennycress (*Thlaspi arvense* L.) from now on referred to as pennycress, is a dicotyledonous winter-annual plant in the Brassicaceae family that is native to Eurasia and over time has become widely distributed throughout the continent of North America (Sedbrook et al., 2014). Historically classified as a weed by producers, and often referred to by alternate names such as "fanweed, stinkweed, or frenchweed," pennycress is now being considered a promising bioenergy oilseed crop for liquid fuel applications in both aircraft and ships by both commercial industry and the United States military (Warwik et al., 2002; Moser et al., 2009; Sindelar et al., 2017). Pennycress has high seed production potential with the number of seeds produced on a single plant ranging from approximately 13,000 to 15,000 (Hume, 1990). In mechanically harvested pennycress plots in Illinois, seed yield was approximately 1400 kg ha^{-1} with a 360 g kg^{-1} seed oil content (Isbell, 2009).

Erucic (22:1) and linoleic (18:2) acids are the primary components that make up pennycress seed oil at 32.8% and 22.4%, respectively (Moser et al., 2009). Pennycress oil has superior fluidity at low temperatures when compared with soybean oil, making it better suited in industrial applications where low temperatures are prevalent. The overall kinematic viscosity of pennycress oil was determined to be higher than soybean at temperatures ranging from 25 to 100°C indicating superior lubricating capabilities over a wide temperature range (Moser et al., 2009). Though beneficial for lubrication, this high kinematic viscosity is at the upper threshold of what is desirable in liquid fuel applications, and is a key aspect receiving attention from breeders for refinement and reduction in the future (Moser, 2012; Sedbrook et al., 2014).

Pennycress is an attractive potential new crop to producers because of high winter hardiness which allows it to successfully overwinter at temperatures as low as -30°C, and early maturity, resulting in early harvest and a long post-harvest growing season remaining, ideal for intercropping or double-cropping (Sedbrook et al., 2014; Dose et al., 2017). An additional characteristic of pennycress that makes it desirable in intercropping situations is the fact that on many winter annual lines, silicles do not form on the first 25-cm of the stem, thus allowing room for harvest of the mature pennycress over the top of recently emerged relay-sown soybean seedlings (Sedbrook et al., 2014). Sown in the fall, pennycress can either be intersown into a standing crop or sown post-harvest after early maturing traditional crops (Dose et al., 2017).

Early-maturing traditional crops would include cool-season crops, short-life cycle warm-season crops such as buckwheat (*Fagopyrum esculentum* L.) and proso millet (*Panicum milaceum* L.), and early maturity sunflower (*Helianthus annuus* L.) hybrids, and soybean cultivars. In a series of pennycress sowing date studies conducted by Dose et al. (2017) from 2012-2015 with sowing dates ranging from late-August through late-October it was determined that in order to maximize pennycress yield and oil content sowing should occur between late-August and late-September. During this range of sowing dates both the highest yield and oil content were obtained at 1109 kg ha^{-1} and 360 g kg^{-1}, respectively. As soon as the sowing dates were delayed both traits were reduced substantially.

Following fall sowing and stand establishment, pennycress plants overwinter as vegetative rosettes, resume growth in the early spring, bolt, flower, develop seed, and can be harvested in early-to mid-June (Isbell, 2009). The winter-annual life cycle allows pennycress to serve as both a cover crop in the establishment season and an industrial commodity in the second season; while having minimal impact on the primary commodity of soybean (Johnson et al., 2015). In a study conducted by Bishop and Nelson (2019) from 2014-2016 pennycress was intersown into corn at growth stages V4, V6, R5, and R6, respectively; in addition to one treatment having pennycress sown post-corn-harvest. Within the same year corn grain yield of all treatments was similar to the corn grain yield of the monocropped check treatment. The only significance indicated was between years, with corn grain yields in 2014 yielding higher than those of 2015 and 2016, which were similar. Following the harvest of pennycress in the subsequent growing seasons, soybean was planted into these treatments in order to analyze the impact a previous crop of pennycress had on double-cropped soybean seed yield. Within the same year, all double-cropped treatments produced soybean seed yields similar to, or higher than the soybean seed yield of the monocropped check treatment. Soybean seed yields in 2016 and 2017 were similar, while excessive rainfall in 2015 resulted in lower soybean seed yield across treatments. Pennycress seed yields in this experiment ranged between 56 kg ha^{-1} and 253 kg ha^{-1} from an average plant density at harvest of 64 plants m^{-2}. This seed yield was obtained from a wild-type of pennycress, and though low yielding, the authors concluded that due to no yield reduction in the principal crops of corn and soybean, this cropping system would be feasible if a higher yielding pennycress line could be obtained (Bishop and Nelson, 2019).

A unique benefit that pennycress provides producers in addition to acting as a cover crop while simultaneously providing an additional commodity value in the subsequent growing season is providing weed control within a cropping system. In experiments conducted by Johnson et al. (2015) in 2011 and 2012, one component was to determine the effect that pennycress seeding rate, line, and sowing date have on weed biomass and weed cover within treatments. Results determined that the presence of pennycress within a treatment reduced weed biomass over 80% in comparison to the control; regardless of which seeding rate (5.5 kg ha^{-1} or 11 kg ha^{-1}) was used. In addition, it significantly reduced the amount of weed cover present. In this same experiment, similar results were found regarding pennycress sowing date and selected lines for two sowing dates (August and September) and two breeding lines of pennycress (MN 106 and NY). In these treatments a 95% reduction in weed biomass was obtained with the pennycress treatments in comparison with the control. The fact that significant weed suppression was obtained in these trials with negligible influence from seeding rate, sowing date, and line selection led the authors to infer that pennycress may have substantial allelopathic properties and could be integral in certain weed management systems. This agrees with what Vaughn et al. (2006) determined from testing 15 different “glucosinolate-containing seed meals” through a growth chamber pot study on wheat (*Triticum aestivum* L.) and sicklepod (*Senna obtusifolia* L.) emergence; one of which was pennycress seed meal. Through this experiment pennycress seed meal provided 100% control of wheat and sicklepod at concentrations within the soil of 0.1 and 1.0% w/w, respectively. It was concluded by the authors that the presence of a specific glucosinolate is what provided pennycress seed meal with these allelopathic properties.

An additional potential benefit of pennycress is the ability for it to act as a nectar and pollen source for pollinating insects early in the growing season (Eberle et al., 2015). At northern latitudes, this attribute can be essential in allowing resident populations of pollinating insects to survive as they come out of hibernation, and can also benefit seasonal hives of insects such as honey bees by allowing their return earlier in the calendar year from southern overwintering areas. In a study conducted by Eberle et al. (2015) the potential for pennycress, along with two other winter annual crops; winter camelina and winter canola (*Brassica napus* L.) to act as floral nectar sources for pollinating insects was assessed. Results revealed that during the three-week flowering period of pennycress, flies *(Diptera)* were the most frequent visiting insects accounting for 73% of visits. Measured nectar production from pennycress flowers was quite low (12 kg ha^{-1}) in comparison with winter camelina (100 kg ha^{-1}) and winter canola (82 kg ha^{-1}), indicating pennycress is inadequate for providing sustaining insect nectar. However, regardless of nectar production it was clear from both the frequency and duration of insect visitations that pennycress flowers were beneficial.

Winter camelina

Winter camelina, from now on referred to as camelina, has origins tracing back to southeastern Europe and southwest Asia with records indicating cultivation dating back to 4000 B.C. (Berti et al., 2016). Camelina, an oilseed crop in the Brassicaceae family exhibits high winter hardiness that allows survival and seed production at northern latitudes. As a low input winter-annual, with high seed oil content, camelina has gained popularity in the biofuels market, including the military and commercial aviation fuel industry (Gesch and Cermak, 2011; Sindelar et al., 2017). Documented oil content of camelina seed ranges from 380 to 430 g kg^{-1}, along with a protein content ranging from 270 to 320 g kg^{-1} (Gugel and Falk, 2006). Recent research indicates that camelina can successfully be grown in the upper Midwest in both double-and-relay systems with yields ranging between 1100 and 1300 kg ha^{-1} (Gesch et al., 2014). This is in addition to the value it provides as an overwintering cover crop, providing both soil armor and exhibiting competitive nutrient scavenging abilities for N and P (Berti et al., 2017). Prior to the attention to camelina as a cover crop and knowing the full extent of its winter hardiness, winter rye was practically the only winter-hardy cover crop in use throughout this region. Camelina as a promising viable cover crop with additional monetary value as a commodity (Berti et al., 2016), will provide producers an additional option to use as a cover crop and cover crop mixture component; both of which will increase cropping system diversity (Berti et al., 2016).

In addition to monetary returns, camelina acts as an early floral source for pollinators. Late-April through early-June is when camelina flowering occurs, during this same time period native insects are exiting hibernation and honey bees are being returned to the region for the summer (Eberle et al., 2015). This overlap of events provides these insects with a floral nectar source that would be otherwise unavailable. Eberle et al. (2015), through an experiment examining pollinator activity on three different winter annual crops quantified the nectar production of camelina during anthesis at 100 kg ha^{-1}; an amount able to sustain approximately one honey bee colony over the course of one year (Standifer, 1980). This, coupled with the diversified populations of pollinating insects observed visiting camelina flowers led the authors to conclude that camelina has an added value of enhancing pollinator activity (Eberle et al., 2015).

An optimum fall sowing window for camelina in the region of west-central Minnesota as determined by Gesch and Cermak (2011) was deemed to be between early-to mid-October. With this sowing window, both seed yield and oil content were maximized. In their trials, the authors sowed two different camelina cultivars at four sowing dates spaced in intervals of 10-14 days between early-September and mid-October. Both seed yield and oil content increased as sowing was delayed; peaking with early-October sowing. Additionally, the authors observed exceptional weed suppression wherever camelina stands were ideal. They attributed this to both competition and shading provided by camelina, and inferred that some weed suppression may be due to known allelopathic properties (Lovett and Jackson, 1980; Gesch and Cermak 2011).

In certain instances, early sowing dates of camelina are desired by growers to fit their specific cropping system. In cases such as these it was determined by (Berti et al., 2017) through an experiment consisting of four different sowing dates, that as long as camelina is sown after the V3 to V4 growth stages in soybean, and V4 to V5 growth stages in corn; competition between camelina and the respective primary crop is avoided. In this same study (Berti et al., 2017) also determined that camelina sown post-harvest of the respective primary crop had better winter survival rates and consequently better spring stands than camelina intersown into standing corn or soybean. These results reinforce the findings of Gesch and Cermak (2011) that found early-to mid-October to be the optimum fall sowing window for camelina in the region of west-central Minnesota.

In intercropping systems where a primary crop such as soybean is relayed into camelina prior to its bolting stage, a factor that is crucial for the successful harvest of camelina is the "height differential" between the two crops at the time of camelina harvest (Gesch et al., 2014). This is due to the fact that to harvest camelina seed and incur the least amount of damage possible on the primary crop (soybean), the combine header must stay at a height slightly above the primary crop. A fortunate characteristic that camelina has which helps in its harvest is the fact that seed production occurs on only the upper third to half of the plant (Gesch et al., 2014). Countless factors throughout the growing season can influence this difference in height making it varied from year to year. In 2010 and 2011 respectively, Gesch et al. (2014) observed camelina and relay-sown soybean plant heights of 26.7 cm and 80 cm, and 23.8 cm and 74.4 cm at the time of camelina harvest. Harvest timing of camelina is also crucial in capitalizing on seed oil content while simultaneously mitigating harvest loss. Sintim et al. (2016) concluded that direct harvesting camelina between BBCH stages 807 and 808 (70-80% ripe silicles on the plant) Martinelli and Galasso (2011) provides this balance.

Winter rye

Winter rye (*Secale cereale* L.), from now on referred to as rye is a popular cover crop choice among producers in the upper Midwest (Moore et al., 2013). A member of the grass family, rye has high winter hardiness which allows it to successfully withstand the harsh winters experienced at northern latitudes (Stoskopf, 1985). This is due in part to anti-freeze like proteins produced in the rye leaves which are secreted into the leaf's apoplast and accumulated around the meristem (Griffith et al., 1992). In addition to winter hardiness, rye also breaks dormancy and begins regrowth early in the spring resulting in high biomass production early in the growing season; an important attribute for producers intending forage production (Maloney et al., 1999). Additionally, in certain crop production settings, rye can aid in weed suppression through allelopathy and also as a surface residue barrier (De Bruin et al., 2005).

Nitrogen management and retention is also improved with the integration of rye as a cover crop due to its ability to scavenge excess nitrogen and reduce nitrate leaching. Soil properties including water retention, plant available water, and soil organic matter content are improved with the long-term integration of rye as a cover crop within a cropping system. At field capacity, Basche et al. (2016) observed increases of 10.9% and 10% in soil water content at 0-15 cm and 15-30 cm soil depths, respectively, from long-term integration of rye as a cover crop in a corn-soybean crop rotation. In this same study, overall plant available water increased 21.1% and 21.9%, respectively; which the authors mainly attribute to the increase in soil water content at field capacity. In a nine-year experiment, when rye was sown following harvest of the main crop, Moore et al. (2013) discovered soil organic matter increases of 15% and 5% in the top 0-5 cm and 5-10 cm soil depths, respectively. Although increases in soil organic matter can be challenging to quantify and attribute exclusively to the integration of rye in a cropping system, utilizing rye as a cover crop has been directly associated with increased soil organic matter levels (Moore et al., 2013).

CROPPING SYSTEMS OVERVIEW

The cropping systems soybean-soybean-corn (System-I) and corn-soybean-corn (System- II) each spanned three growing seasons or years noted as Year-1, Year-2, and Year-3 and were conducted during 2016, 2017, and 2018. In Year-1, soybean and corn were sown as primary crops in separate experiments that represented System-I and System-II, respectively. During the late summer to early fall, the winter annual cover crops pennycress, camelina, and rye were individually intersown into both of the Year-1 experiments to allow establishment before overwintering. In Year-2, soybean was relay-sown into the winter annual cover crops established in the Year-1 experiments; except the rye, which was terminated with glyphosate [N-(phosphonomethyl) glycine] prior to sowing of the soybean in Year-2. In the early summer of Year-2, pennycress and camelina were harvested over the top of the soybean plants once they had reached their respective harvest maturities. The soybean relayed during Year-2 was harvested in the fall. In Year-3, corn was no-till sown into both Year-2 experiments. The integrity of the cropping systems was maintained on an individual plot basis from year to year. At completion of the systems in Year-3 the entire series of experiments provided two cropping systems: System-I soybean-soybean-corn and System-II corn-soybean-corn with winter annual cover crops intersown during Year-1 and harvested for seed during Year-2. This thesis is written exclusively on Year-2 of each cropping system.

OBJECTIVES

I.) Determine if pennycress, camelina, or rye are effective intersown cover crop options in soybean-soybean-corn and corn-soybean-corn crop sequences.

II.) Determine if pennycress, camelina, or rye compete with soybean for soil water, and if this can be directly linked to yield reduction in soybean.

III.) Determine if the additional seed yield obtained from the pennycress and camelina makes them economically viable to utilize as intersown cover crops in intercropping systems with primary crop sequences of soybean-soybean-corn and corn-soybean-corn in eastern North Dakota.

MATERIALS AND METHODS

Experiments were conducted at Prosper (47 00' N, -97 11' W, elevation 284 m), and Casselton, North Dakota (46 88' N, -97 25' W, elevation 286 m) in 2017 and 2018 on field areas without tile drainage. During the 2017 growing season, two experiments (System-I Year-2 and System-II Year-2) were conducted at Prosper, and in 2018 the same two experiments were conducted at Prosper and Casselton. Soils at Prosper are a complex of Perella (fine-silty, mixed, superactive, frigid Typic Endoaquolls) and Bearden (fine-silty, mixed, superactive, frigid Aeric Calciaquolls), while Casselton has the Fargo soil series (Fine, smectitic, frigid Typic Epiaquerts) (Soil Survey Staff, 2005; Soil Survey Staff, 2014; Soil Survey Staff, 2016).

All experiments were conducted using a randomized complete block design with four replicates. A total of ten treatments were within each replicate, nine of which were associated with three cover crops sown at three dates in a 3×3 factorial arrangement; in addition to one non-treated check (NTC) treatment. Each treatment was contained in an experimental unit area of 20.40 m^2 (four soybean rows spaced at 0.76 m by 6.71 m long; trait collection occurred in the two-center rows of each experimental unit unless specified otherwise. The three winter-annual cover crops were pennycress 'MN106', camelina 'Joelle', and rye 'Rymin'. The pennycress and camelina were acquired from the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) Soil Conservation Laboratory, Morris, MN. The rye was a North Dakota State University (NDSU) cultivar purchased at Agassiz Seed, West Fargo, ND. The cover crop sowing dates for System-I corresponded with soybean growth stages R6 (full seed), R7 (beginning maturity), and R8 (full maturity) and for System-II corn growth stages R4 (dough), R5 (dent), and R6 (physiological maturity) (Kandel, 2010; Ransom, 2013).

Relay-sowing soybean

In the spring of Year-2, soybean was relayed into the established cover crops from Year-1 for both System-I (soybean-soybean-corn) and System-II (corn-soybean-corn) as soon as the risk of frost had subsided, soil temperatures were above 10°C, and field conditions were conducive for sowing (Table 1). At this time, as expected, the pennycress and camelina had broken dormancy and entered the stem elongation/bolting stage 301 (Martinelli and Galasso, 2011). Soybean was sown at a population of 432,434 pure live seeds ha^{-1} using a four-row John Deere Max Emerge planter toolbar outfitted with ALMACO rotary cone metering units and a row spacing of 0.76 m (Deere & Company, Moline, IL; ALMACO, Nevada, IA). Seed was metered into the individual planter row units using properly sized scoops (round plastic bottles cutoff squarely at the top and filled until slightly crowned at the top edge) for the desired population. Row placement in Year-2 was offset slightly (8-10 cm) from Year-1 to avoid residual root and stem material left from the soybean or corn from Year-1. The soybean selected for use in all experiments during Year-1 and Year-2 was the Asgrow AG0835 cultivar. This cultivar has a maturity rating of 0.8, is glyphosate resistant, soybean cyst nematode (*Heterodera glycines* L.) resistant, and has a high tolerance for iron deficiency chlorosis (IDC).

Table 1. Dates in which study management events occurred during 2017 at Prosper; and 2018 at Casselton and Prosper.

Environment †	Soybean sowing ‡§	Cover crop harvest ¶	Soybean harvest #
Casselton 2018	23 May	25 June; 2 July; 12 July	23 Oct
Prosper 2017	12 May	16 June; 21 June; 27 June; 7 July	19 Oct
Prosper 2018	23 May	22 June; 9 July; 10 July	22 Oct

† Environment is defined as one location in one year.

‡ Spring cover crop stand counts taken immediately prior to planting on the same day.

§ Rye treatments terminated with glyphosate on 5 May and 21 May in 2017 and 2018, respectively.

¶ Soil water samples and cover crop stand counts taken immediately following cover crop harvest on the same day. Multiple harvest dates were necessary due to the inconsistency in which pennycress and camelina treatments reached harvest maturity. The majority of pennycress harvest occurred at the earliest cover crop harvest dates listed. Camelina was harvested at the later cover crop harvest dates, in addition to pennycress treatments that took additional time to reach harvest maturity.

Soil water samples and percent green cover taken immediately following soybean harvest on the same day.

Intersown cover crop traits

Immediately prior to relay-sowing soybean, cover crop stand counts were conducted from five random 0.093 m^2 areas for a total area of 0.46 m^2 in the two-center rows of each plot by counting the number of live plants present. Following the relay-sowing of soybean, as the pennycress and camelina progressed through their growth stages, flowering date was recorded based on visual observation of plants within the center-two rows of each respective plot when there was at least one open flower on 50% of the plants in the stand of pennycress or camelina. Flowering date was recorded as number of days after 1 April.

Once harvest maturity of the pennycress and camelina was reached in the System-I and System-II experiments average plant height of both the cover crop and soybean were measured in the center-two rows of each plot, in addition to determining the current soybean growth stage. Visual ratings for seed shattering and plant lodging were also taken exclusively on the pennycress and camelina at this time. Ratings for seed shattering were noted as percentages which represented the amount of visible shattered silicles on plants within the center-two rows of the plot area. Plant lodging was recorded on a 0-9 scale with zero indicating plants standing perfectly erect and nine indicating plants lying completely horizontal within the plot.

Immediately prior to the mechanical harvest of the pennycress and camelina, plant biomass samples were taken from the center-two plot rows in two 0.76-m^2 areas by cutting the plants off at the soil surface and placing them into paper bags. The seed from these samples was returned to the primary seed yield sample after analysis of harvest index. Biomass sample collection only occurred in the experiments conducted at Prosper, thus providing two environments for the analysis of harvest index for the intersown cover crops.

Following the collection of biomass samples the mechanical harvest of the pennycress and camelina was done using a Hege 125B plot combine (Hans-Ulrich Hege Company, Waldenberg, Germany) (Table 1). During this harvest, header height on the combine was maintained so that it stayed at or slightly above the soybean canopy height within each plot. The harvested pennycress and camelina seed was analyzed for seed yield, with subsamples obtained to determine seed water content. Following harvest, cover crop stand counts were conducted from five random 0.093 m^2 areas for a total area of 0.46 m^2 in the two-center rows of each plot by counting the number of living stems present. Pennycress and camelina stand mortality was calculated based off the spring and post-harvest stand counts using the equation: *[(spring stand count - post-cover crop harvest stand count)/spring stand count] *100.* In addition to stand counts occurring at this time, post-harvest soil water samples at depths of 0-30 cm and 30-60 cm were collected from the center-two rows of each plot using a hand soil probe to analyze for differences in soil gravimetric water content (GWC) among intercropping treatments and the NTC treatment. Two soil cores were extracted from each depth within each plot and mixed in a bucket with their common soil core from the same depth to form one composite sample for the 0-30-cm and 30-60-cm depth in each plot.

Following the post-cover crop harvest trait collection, a 1.1 kg a.e. ha^{-1} rate of glyphosate was applied to each plot in all experiments using a CO_2 pressurized backpack hand-sprayer set to a pressure of 276 kPa. During the application, a rate of 80 L ha^{-1} was applied with the applicator walking at an approximate speed of 5 km h^{-1}. Prior to and following this herbicide application, hand weeding as needed was conducted throughout all experiments to control weeds.

The last trait from these experiments pertaining to the intersown cover crops was collected immediately following soybean harvest. Percent green cover was measured at this time using the Canopeo © application set to its default settings in order to analyze the green cover contribution obtained from the volunteer cover crop seed that had established since its harvest (Canopeo, Oklahoma State University, Stillwater, OK). This was done in both the System-I and System-II experiments at the end of Year-2 in two areas within the center-two rows of the plot at a height of 1 m.

Soybean traits

The soybean in the System-I Year-2 and System-II Year-2 experiments were harvested when they reached harvest maturity (Table 1). Prior to harvest, average plant height was measured, and plant lodging visually rated on a 0-9 scale with zero indicating plants standing perfectly erect and nine indicating plants lying completely horizontal within the plot. In addition, stand counts were recorded from 1-m sections of each of the two-center plot rows by counting the stems of the physiologically mature soybean plants. Soybean was mechanically harvested using a Hege 125B plot combine with seed yield and 1000-seed weight determined for each plot. Following soybean harvest, soil water samples at depths of 0-30-cm and 30-60-cm were collected from each plot using a hand soil probe to analyze for differences in GWC among intercropping treatments and the NTC treatment. Two soil cores were extracted from each depth within each plot and mixed in a bucket with their common soil core from the same depth to form one composite sample for the 0-30-cm and 30-60-cm depth in each plot.

Processing procedure for cover crop seed yield, seed water content, and harvest index

The harvested pennycress and camelina yield and biomass samples were taken from the field and dried, in drying chambers in Waldron Hall on the NDSU campus, at a temperature of 43°C until all samples reached 30 g kg^{-1} water content. Yield samples were first cleaned using a Clipper "Office Tester" model seed cleaner and then transferred into paper bags of equal mass for the remainder of their analysis (Clipper, A.T. Ferrell Company, Bluffton, IN). These samples were then weighed to determine plot yield; and their weights corrected to represent yield at a seed water content of 85 g kg^{-1}. Subsamples to determine seed water content had been taken at the time of harvest and weighed wet immediately after harvest was complete. The samples were then dried in an oven at 106°C for 48 h^{-1} in order to ensure near zero water content had been reached. At this point, the samples were weighed dry in order to complete the harvest seed water content calculation on a wet basis. After analysis the seed weight from these subsamples was added into the corrected yield equation. The biomass samples were taken from the drying chamber and hand threshed in order to separate the seed from the plant residue. Once threshed the seed was cleaned using a hand screen cleaner and weighed in order to complete the harvest index calculation. This seed weight was then added into the corrected yield equation.

Processing procedure for soybean seed yield and 1000-seed weight

The harvested soybean yield samples were dried and cleaned using the same methodology as the pennycress and camelina yield samples. Once cleaned, these samples were transferred into paper bags of equal mass and weighed in order to calculate plot yield; with their weights corrected to represent yield at a water content of 130 g kg^{-1}. At this point, a subsample in the quantity of exactly 200 seeds was counted for determining 1000-seed weight. This subsample was then weighed, and the resultant weight was multiplied by a factor of 5 in order to obtain 1000-seed weight data.

Processing procedure for soil water samples

The soil water samples taken both after cover crop harvest and soybean harvest were collected and processed using identical methodology. Two soil cores were collected from each depth (0-30 and 30-60 cm) within the center-two rows of each plot. These two cores were placed together in a bucket and thoroughly mixed to form one representative sample at each depth. This sample was then placed in a Ziploc © bag and immediately upon arrival back to campus, weighed, in order to record the wet weight. These samples were then placed in an oven at a temperature of 106°C for 48 h^{-1} to ensure all water was removed from the soil. The samples were then taken from the oven, weighed, and their dry weight recorded in order to complete the calculation of gravimetric water content on a dry weight basis.

Statistics

Each of the System-I Year-2 and System-II Year-2 experiments were analyzed individually and combined with their common experiment in other years based on homogeneity of trait variances. The term environment is defined as one location in one year and was a random effect in the statistical model. The intercropping treatments consisting of cover crop type and sowing date were fixed effects in the statistical model. Homogeneity of variance was tested by Bartlett's χ^2 at $(P \leq 0.05)$. Means separation was performed using *F*-protected LSD means comparisons at the $P \leq 0.05$ level of probability.

Within System-I Year-2 all data for the traits directly related to the winter annual cover crops were analyzed as a 2x3 factorial arrangement of a randomized complete block design since they were collected exclusively from the three sowing date treatments of pennycress and camelina. The soybean traits and soil GWC were analyzed as a randomized complete block design since data for these traits was collected from the NTC; in addition to the nine treatments generated from the 3×3 factorial arrangement of winter annual cover crop and sowing date.

Analysis within System-II Year-2 differed slightly from the previously stated methodology of analysis for System-I Year-2 due to two environments of data missing for the intersown cover crop, camelina (Table 2).

Table 2. Indication of which environments had intersown cover crop traits obtained for the System-II Year-2 cropping system.

	Environment		
	Casselton 2018 †	Prosper 2017	Prosper 2018 †
Cover crop			
Pennycress	Obtained	Obtained	Obtained
Camelina	—	Obtained	—

† Slow stand establishment resulted in similar plant heights of the camelina and soybean at the time of camelina reaching harvest maturity, thus preventing mechanical harvest of the camelina.

Due to the events described in Table 2, the three environments of pennycress data were combined and analyzed as a randomized complete block design. The Prosper 2017 environment of camelina data was analyzed individually as a randomized complete block design and is presented separately. The soybean traits and soil GWC were combined across environments and analyzed as a randomized complete block design since data for these traits was collected from the NTC; in addition to the factorial arrangement of winter annual cover crop and sowing date. Sources of variation, degrees of freedom, and expected mean squares for single environments and combined environments are shown in Tables 3, 4, 5, and 6, respectively.

Table 3. Sources of variation (SOV), degrees of freedom (df), and expected mean squares (EMS) for the intersown cover crop traits collected for a single environment of the intercropping study conducted in 2017 and 2018 in North Dakota.

SOV	df	EMS
Rep	3	—
Sowing date	2	$\sigma^2_\varepsilon + rc\sigma^2_S$
Cover crop	1	$\sigma^2_\varepsilon + rs\sigma^2_C$
S × C	2	$\sigma^2_\varepsilon + r\sigma^2_{SC}$
Error	15	σ^2_ε

S=Sowing date, C=Cover crop

Table 4. Sources of variation (SOV), degrees of freedom (df), and expected mean squares (EMS) for the combined analyses of intersown cover crop traits collected across three environments for the intercropping study conducted in 2017 and 2018 in North Dakota.

SOV	df	EMS
Environment †	2	—
Rep (ENV)	9	—
Sowing date	2	$\sigma^2_\varepsilon + rc\sigma^2_{ES} + rec\sigma^2_S$
ENV × S	4	$\sigma^2_\varepsilon + rc\sigma^2_{ES}$
Cover crop	1	$\sigma^2_\varepsilon + rs\sigma^2_{EC} + res\sigma^2_C$
ENV × C	2	$\sigma^2_\varepsilon + rs\sigma^2_{EC}$
S × C	2	$\sigma^2_\varepsilon + r\sigma^2_{ESC} + re\sigma^2_{SC}$
ENV × S × C	4	$\sigma^2_\varepsilon + r\sigma^2_{ESC}$
Error	45	σ^2_ε

† Environment=ENV, S=Sowing date, C=Cover crop

Table 5. Sources of variation (SOV), degrees of freedom (df), and expected mean squares (EMS) for the soybean and soil water traits collected for a single environment of the intercropping study conducted in 2017 and 2018 in North Dakota.

SOV	df	EMS
Rep	3	—
Treatment	9	$\sigma^2_\varepsilon + r\sigma^2_T$
Error	27	σ^2_ε

Table 6. Sources of variation (SOV), degrees of freedom (df), and expected mean squares (EMS) for the combined analyses of the soybean and soil water traits collected across three environments for the intercropping study conducted in 2017 and 2018 in North Dakota.

SOV	df	EMS
Environment	2	—
Rep (ENV)	9	—
Treatment	9	$\sigma^2_\varepsilon + r\sigma^2_{ET} + re\sigma^2_T$
ENV × Treatment	18	$\sigma^2_\varepsilon + r\sigma^2_{ET}$
Error	81	σ^2_ε

† Environment=ENV

RESULTS AND DISCUSSION

At the Casselton 2018 environment, the growing season began with below normal rainfall during May where monthly rainfall was 49.0 mm below the long-term average (Table 7). The months of June through October alternated between rainfall amounts that were either above the long-term average, or slightly below the long-term average. June rainfall was 20.1 mm above the long-term average, followed by rainfall that was 0.3 mm below the long-term average in July (Table 7). Rainfall during August was 61.5 mm above the long-term average and was the greatest amount of rainfall received at this environment. September rainfall was 4.0 mm below the long-term average, and October, the final month of the growing season received rainfall of 28.5 mm above the long-term average.

The below average rainfall received in May coupled with a monthly average temperature of 3°C above normal could have been contributing factors to the mortality observed in the intersown pennycress and camelina between the time they resumed growth in the spring and were harvested. Adequate soil water during this period is important as both the pennycress and camelina were rapidly growing through their late vegetative, flowering, and seed development stages. The above average rainfall in June would have been of great benefit to both the pennycress and camelina, as well as the relay-sown soybean. The pennycress and camelina would have been going through later seed development stages and senescing during this time period and above average rainfall could have aided in attaining maximum yield potential of the pennycress and camelina plants.

As the pennycress and camelina were senescing, the relayed soybean was in early vegetative growth and above average rainfall would have insured successful, uniform, and rapid stand establishment. The above average rainfall in August came at a time when the relay-sown soybean would have been going through the later reproductive stages R5 and R6, beginning seed and full seed, respectively (Kandel, 2010). Above average rainfall during these growth stages reduced water stress on the soybean plants and allowed for maximum expression of the yield components, pods plant^{-1}, seeds pod^{-1}, and seed weight.

Table 7. Total monthly rainfall, temperature, and departure from normal for three environments at Casselton, and Prosper, North Dakota, in 2017 and 2018.

		Rainfall		Temperature			
Environment	Month	Total	±Normal†	Max.	Min.	Avg.	±Normal†
		———mm———		——————°C——————			
Casselton 2018	May	30.5	-49.0	25	8	16	+3
	June	127.5	+20.1	27	15	21	+2
	July	81.0	-0.3	27	15	21	0
	Aug	127.5	+61.5	26	12	19	-1
	Sept	62.0	-4.0	20	7	14	-1
	Oct	82.6	+28.5	9	-2	3	-4
Prosper 2017	May	16.8	-60.7	21	6	13	0
	June	87.9	-12.4	27	12	19	+1
	July	50.0	-37.8	28	14	21	0
	Aug	52.6	-14.0	25	11	18	-2
	Sept	151.6	+86.1	22	8	16	+1
	Oct	6.9	-54.9	15	0	8	0
Prosper 2018	May	53.8	-23.6	25	9	17	+3
	June	79.2	-21.1	27	14	21	+2
	July	65.3	-22.6	27	14	20	-1
	Aug	78.5	+11.9	27	12	19	-1
	Sept	70.9	+5.3	21	7	14	-1
	Oct	66.5	+4.8	9	-1	4	-3

Weather data obtained from: https://ndawn.ndsu.nodak.edu/weather-data-monthly.html
†Based on 1981-2010 long-term averages

The Prosper 2017 environment was chronically deficient in rainfall throughout the months of May through August (Table 7). In May, rainfall was 60.7 mm below the long-term average, June had a rainfall total that was 12.4 mm below the long-term average (Table 7). July and August were 37.8 and 14.0 mm below the long-term rainfall average, respectively. Rainfall for the month of September was above the long-term average by 86.1 mm, relieving some of the rainfall deficiency incurred during the previous four months. This trend was not long lasting however, with rainfall for the month of October being 54.9 mm below the long-term average. This lack of rainfall placed stress on both the intersown pennycress and camelina, as well as the relay-sown soybean. Mortality experienced in the stands of pennycress and camelina between the time they broke dormancy in the spring and were harvested was likely due in part to this lack of rainfall that would also affect their harvested seed yield. The relay-sown soybean at this environment experienced delayed germination and stand establishment because of drier soil conditions. Soybean seed yield of treatments was highly varied at this environment, and was likely influenced by infrequent rainfall received throughout the majority of the growing season.

Rainfall at the Prosper 2018 environment was below the long-term average for the months of May through July and above the long-term average for the months of August through October (Table 7). Rainfall was 23.6, 21.1, and 22.6 mm below the long-term average for May, June, and July, respectively, and 11.9, 5.3, and 4.8 mm above the long-term average for August, September, and October, respectively. The chronic below average rainfall from May through July coupled with average temperatures in May and June that were 3 and 2°C above normal, respectively, likely caused spring stand losses for pennycress and camelina. Additionally, pennycress and camelina yield potential would have been reduced as the months of May and June were when the pennycress and camelina were progressing through their late-vegetative and early-to mid-reproductive stages before senescing in late-June or early-July.

The relay-sown soybean would have experienced water stress early in the growing season, possibly hindering germination and making stand establishment a challenge. Above average rainfall in August could have been beneficial to soybean which was progressing through seed development stages R5 and R6. However, due to the prevailing lack of rainfall in the previous months, it is likely that above average August rainfall had little benefit in maximizing the yield component, pods plant $^{-1}$, but may have benefited seeds pod^{-1} and seed weight.

Soybean-soybean-corn crop sequence (System-I, Year-2)

Intersown cover crop traits

Statistical analysis across three environments for 11 cover crop traits, in addition to soybean plant height and growth stage at the time of cover crop harvest are shown in Table 8. The design for this analysis is a 2x3 factorial arrangement of a randomized complete block with two cover crops and three sowing dates. Pennycress and camelina were intersown into soybean at three dates corresponding with soybean growth stages R6, R7, and R8 during the previous growing season. Pennycress and camelina then established, overwintered, and resumed growth in the subsequent growing seasons of 2017 and 2018. This discussion pertains to trait responses after overwintering and breaking spring dormancy.

Table 8. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the combined analyses across three environments of 11 intersown cover crop traits, in addition to soybean plant height and growth stage at cover crop harvest, collected in the System-I Year-2 intercropping study conducted in 2017 and 2018 in North Dakota.

		Mean square												
SOV	df	Flowering date	Cover crop plant height at harvest	Soybean plant height at cover crop harvest	Soybean growth stage at cover crop harvest	Shatter	Lodging	Spring plants m^{-2}	Post-harvest plants m^{-2}	Stand mortality	Seed water	Seed yield	Harvest Index †	Volunteer green cover contribution
Environment †	2	1 629.30	276.3	913.2	5.60	13.60	85.80	232 741	146 795	1289	104 691	289 186	0.47	325.6
Rep (ENV)	9	2.14	34.3	170.8	0.70	7.90	1.12	18 147	11 590	1668	307	26 824	0.002	49.7
Sowing date	2	1.43	181.1*	124.5	1.43	17.90	13.50	33 255	231	575	3 770	32 312	0.01	5.3
ENV × S	4	1.01	22.4	56.5	1.05	5.14	2.50	23 373	5 892	961	2 495	40 319*	0.004	25.2
Cover crop	1	760.50	995.7	8 147.2**	378.62	638.60	116.30	2 400 113	1 164 470	9950	18 966	238 605	0.06	1.6
ENV × C	2	81.79**	1 161.2**	79.2	42.03*	90.40**	27.20**	167 389**	79 838**	5808**	2 871	94 315**	0.03**	137.9**
S × C	2	1.29	113.8	154.5	1.92	4.03	0.80	125 294*	29 919*	932	745	7 212	0.0005	21.3
ENV × S × C	4	5.21	53.0	48.6	2.47**	2.40	1.35	15 833	3 183	564	47	7 367	0.002	12.1
Error	45	2.23	44.5	42.5	0.57	5.80	2.00	15 731	12 869	492	1 710	11 019	0.001	19.1
Total	71													
CV%		3.0	13.7	25.7	16.3	60.6	47.6	35.7	57.6	46.7	18.9	33.4	14.3	65.8

*, ** significant at 0.05 and 0.01 level, respectively

† Two environments of data were collected for the trait, harvest index, rather than three

S=Sowing date, C=Cover crop

Flowering date

Analysis across environments indicated the environment by cover crop interaction was significant for cover crop flowering date (Table 8). Flowering date (days after 1 April) was 4, 11, and 4 days earlier for pennycress compared with camelina at the Casselton 2018, Prosper 2017, and Prosper 2018 environments, respectively (Table 9). Pennycress and camelina flowering dates were 18 and 11 days earlier, respectively, at the Prosper 2017 environment than either of the 2018 environments indicating a magnitude interaction response (Table 9). Canola growing degree day accumulations on 1 May in 2017 and 2018 were 234 and 120, respectively (data not shown), and are associated with fewer days to flowering for both crops at the Prosper 2017 environment due to warmer spring temperatures in 2017 than 2018 (NDAWN, 2019).

Table 9. Mean calendar days required for pennycress and camelina to reach 50% flowering, averaged across three sowing dates at three environments in North Dakota.

	Environment		
Cover crop	Casselton 2018	Prosper 2017	Prosper 2018
	calendar days after 1 April		
Pennycress	52.0	34.0	52.0
Camelina	56.0	45.0	56.0
LSD (0.05)		1.2	

Intersown cover crop plant height

The environment by cover crop interaction was significant for cover crop plant height at harvest (Table 8). The interaction was caused by a change in rank and magnitude for pennycress and camelina height differences among the three environments. Camelina plant height at harvest was 8.9-and 21.1-cm greater than pennycress at the Casselton 2018 and Prosper 2018 environments, respectively, but 7.6-cm less than pennycress at the Prosper 2017 environment (Table 10). Soybean plant height at the time of pennycress and camelina harvest was 15 and 36 cm, respectively (data not shown).

Table 10. Mean harvest plant height of pennycress and camelina, averaged across three sowing dates at three environments in North Dakota.

	Environment		
	Casselton 2018	Prosper 2017	Prosper 2018
Cover crop			
		cm	
Pennycress	41.3	51.9	41.9
Camelina	50.2	44.3	63.0
LSD (0.05)		5.5	

The height differential between the pennycress, camelina, and soybean is crucial for a successful harvest of both the respective intersown cover crop and soybean. Without an adequate height differential harvest of the intersown cover crop seed over top of the soybean becomes a challenge, and occasionally impossible without damage occurring to the soybean from the harvester platform and cutter bar. Sedbrook et al. (2014) states that silicles on pennycress do not form on the first 25-cm of stem, while Gesch et al. (2014) determined that seed production only occurs on the upper one-third to one-half of a camelina plant. If producers implemented this cropping system it would be crucial to maintain combine platform height in accordance with the height differential experienced between the intersown cover crop and relay-sown soybean.

At the Casselton 2018, Prosper 2017, and Prosper 2018 environments the mature pennycress was 26.3-, 36.9-, and 26.9-cm taller, respectively than the averaged soybean plant height of 15 cm. Camelina plant height at the Casselton 2018, Prosper 2017, and Prosper 2018 environments were 14.2-, 8.3-, 27-cm taller, respectively than the averaged soybean plant height of 36 cm (Table 10). In a similar study conducted by Gesch et al. (2014), the height differential between intersown camelina and soybean in a relay-crop system was measured. In the first year of the study camelina and soybean plant heights were 80 and 26.7 cm, respectively, while in the second year of the study they were 74.4 and 23.8 cm, respectively; resulting in camelina being 53.3-and 50.6-cm taller than soybean in each year of the study, respectively.

Relay-sown soybean growth stage at the time of cover crop harvest

The environment by cover crop interaction was significant for the relay-sown soybean growth stage at the time of cover crop harvest (Table 8). Across all environments, due to the majority of pennycress being harvested at the earliest cover crop harvest dates listed in Table 1, soybean was at an earlier growth stage compared to the later cover crop harvest dates at which camelina harvest occurred (Table 1, Table 11). Harvest of pennycress occurred at all environments when soybean was at a similar growth stage, V2, at both the Casselton and Prosper 2018 environments, and V3 at the Prosper 2017 environment, respectively (Kandel, 2010) (Table 11). At the Prosper 2017 environment, camelina was harvested when soybean was at the V5 growth stage, while at both the Casselton and Prosper 2018 environments camelina was harvested when soybean was at the later R2 growth stage (Kandel, 2010) (Table 11).

Table 11. Mean relay-sown soybean growth stage at the time of pennycress and camelina harvest, averaged across three sowing dates at three environments in North Dakota.

	Environment		
Cover crop	Casselton 2018	Prosper 2017	Prosper 2018
		soybean growth stage†	
Pennycress	2.0	3.0	2.0
Camelina	8.0	5.0	8.0
LSD (0.05)		1.0	

† Numerical values 1, 2, 3, 4, 5, and 6 correspond with vegetative growth stages V1-V6. Numerical values 7 and 8 correspond with reproductive growth stages R1 and R2. (Kandel, 2010). Reproductive growth stage R1 began following vegetative growth stage V6, thus why stage R1 follows stage V6.

The harvest of camelina occurring while soybean was at an earlier growth stage at the Prosper 2017 environment could be due to a more rapid accumulation of canola growing degree days early in the growing season during 2017 than what occurred in 2018 due to warmer spring temperatures. Canola growing degree day accumulations on 1 May in 2017 and 2018 were 234 and 120, respectively (NDAWN, 2019). The consistent harvest of pennycress at an earlier soybean growth stage than harvest of camelina could be a desirable characteristic in intercropping systems because of decreased potential for interspecific competition between the intersown cover crop and relay-sown primary crop of soybean; and also decreased potential for damage and stress to occur on the primary crop of soybean from harvest of the intersown cover crop.

Intersown cover crop stand counts and stand mortality

Analysis across environments indicated the environment by cover crop interaction was significant for spring and post-cover crop harvest stand counts and stand mortality (Table 8). Spring pennycress stands were 400, 152, and 511 plants m^{-2} greater than camelina stands at the Casselton 2018, Prosper 2017, and Prosper 2018 environments, respectively (Table 12). Spring pennycress stands were different among environments, while camelina stands were similar.

Table 12. Mean spring stand counts of pennycress and camelina, averaged across three sowing dates at three environments in North Dakota.

	Environment		
Cover crop	Casselton 2018	Prosper 2017	Prosper 2018
	plants m^{-2}		
Pennycress	573	335	692
Camelina	173	152	181
LSD (0.05)		103	

Post-harvest pennycress stands were 174, 202, and 386 plants m^{-2} greater than camelina stands at the Casselton 2018, Prosper 2017, and Prosper 2018 environments, respectively (Table 13). The pennycress stand at the Prosper 2018 environment was greater than either the Casselton 2018 or Prosper 2017 environments, while camelina stands were similar across environments.

Post-harvest stands in this experiment were obtained from fall sowing rates of 16.8 and 11.2 kg ha^{-1} for pennycress and camelina, respectively. In related research, Johnson et al. (2015) had harvest stand counts of pennycress ranging between 133 and 532 plants m^{-2} using a fall sowing rate of 11 kg ha^{-1} across multiple environments of a double-cropping experiment with soybean. In an intercropping experiment with camelina and soybean Gesch et al. (2014) had consistent camelina stands at harvest between 214 and 219 plants m^{-2} from a fall sowing rate of 6.7 kg ha $^{-1}$.

Table 13. Mean post-harvest stand counts of pennycress and camelina, averaged across three sowing dates at three environments in North Dakota.

	Environment		
	Casselton 2018	Prosper 2017	Prosper 2018
Cover crop			
		plants m^{-2}	
Pennycress	278	223	471
Camelina	104	21	85
LSD (0.05)		93	

Stand mortality that occurred between spring and post-harvest stand counts of pennycress and camelina was similar between crops at the Casselton 2018 environment (Table 14). Stand mortality was 54%, and 23% higher for camelina than pennycress at the Prosper 2017 and 2018 environments, respectively. The Casselton and Prosper 2018 environments experienced camelina stand mortality that was similar, while camelina stand mortality at the Prosper 2017 environment was higher. Pennycress stand mortality was similar across the three environments.

Table 14. Mean spring to post-harvest stand mortality for pennycress and camelina, averaged across three sowing dates at three environments in North Dakota.

	Environment		
	Casselton 2018	Prosper 2017	Prosper 2018
Cover crop			
		%	
Pennycress	47	29	32
Camelina	39	83	55
LSD (0.05)		18	

Various factors could have contributed to the observed pennycress and camelina stand mortalities. Since broadcast and light incorporation was the method used for intersowing in the previous fall, stand establishment factors such as sowing depth and plant spacing may have not been adequate for the continued survival of established plants through physiological maturity. In all environments, rainfall was below the long-term average at the beginning of the growing season when pennycress and camelina were breaking dormancy (Table 7). Pennycress and camelina plant injury could have occurred from disruption by the planter units and tractor wheels during the relay-sowing of soybean, potentially impacting stand mortality. Self-thinning could have also occurred within the stands of pennycress and camelina. Though no research is published regarding self-thinning in pennycress and camelina specifically, it is known that self-thinning occurs in other Brassicaceae family crops such as canola, especially at high populations (Van Deynze et al., 1992). Additionally, intra and interspecific competition for resources (sunlight, water, and space) could have also been contributing factors to stand mortality.

Intersown cover crop seed yield

Analysis across environments indicated the environment by cover crop interaction was significant for seed yield of the intersown cover crops, pennycress and camelina (Table 8). Pennycress at the Prosper 2017 and 2018 environments yielded 222 and 194 kg ha^{-1} more than camelina, respectively (Table 15). Similar pennycress and camelina yields of 395 and 458 kg ha^{-1} were harvested at the Casselton 2018 environment. Pennycress yields at the Casselton and Prosper 2018 environments were similar, while the Prosper 2017 environment had a lower pennycress yield. The lower pennycress yield at the Prosper 2017 environment compared with the 2018 environments can be partially attributed to below average rainfall, as discussed previously. Camelina yields were different among environments, with the highest yield produced at the Casselton 2018 environment. This yield was 392 and 214 kg ha^{-1} greater than camelina yields at the Prosper 2017 and 2018 environments, respectively. The 66 kg ha^{-1} camelina yield produced at the Prosper 2017 environment is likely a result of the below average rainfall received during the growing season, low post-harvest stand, and high in-season mortality that occurred at this environment, compared with the 2018 environments.

Table 15. Mean seed yield of pennycress and camelina, averaged across three sowing dates at three environments in North Dakota.

	Environment		
Cover crop	Casselton 2018	Prosper 2017	Prosper 2018
		kg ha^{-1}	
Pennycress	395	288	438
Camelina	458	66	244
LSD (0.05)		87	

Pennycress and camelina in intercropping systems are subject to many variables that can influence yield. These include initial stand establishment, success of overwintering, soil water availability, unavoidable damage from relay-sowing of the soybean, and competition with the established soybean. Consequently, a wide range of yields have been documented for both crops in similar research experiments, in addition to this study.

In data interpreted from Johnson et al. (2017) seed yield of fall sown pennycress with relay-sown soybean ranged between 60 and 2400 kg ha^{-1} for six site-years in southern Minnesota. In a cropping sequence where soybean was relay-sown into fall sown camelina, Berti et al. (2015) reported camelina seed yield at Prosper and Carrington, ND, and Morris, MN. Yields at the Prosper and Carrington, ND locations were averaged across the two years (2012 and 2013) in which the study was conducted, while camelina seed yields at Morris, MN, were reported by individual year due to lack of trait variance homogeneity. At Prosper and Carrington, ND the average camelina yield was 1484 and 775 kg ha^{-1}, respectively. Camelina yields for Morris in 2012 and 2013 were 334 and 1932 kg ha^{-1}, respectively. In a different study conducted by Gesch et al. (2014) camelina yield consistently was between 1100 and 1300 kg ha^{-1} using the same cropping sequence.

Harvest index

Harvest index was determined at both the Prosper 2017 and 2018 environments and analysis indicated a significant environment by cover crop interaction (Table 8). Harvest index was similar between pennycress and camelina at the Prosper 2017 environment (Table 16). At the Prosper 2018 environment, pennycress had a harvest index 0.13 higher than camelina. For both pennycress and camelina the Prosper 2018 environment had higher harvest indices; 0.27, and 0.17 higher, respectively, than those for the Prosper 2017 environment. This can be attributed to a superior stand of pennycress and lower mortality of camelina in 2018 than 2017, in addition to greater yield produced in both crops in 2018 (Table 15).

Table 16. Mean harvest index of pennycress and camelina, averaged across three sowing dates at two environments in North Dakota.

	Environment	
	Prosper 2017	Prosper 2018
Crop		
Pennycress	0.15	0.42
Camelina	0.12	0.29
LSD (0.05)	0.03	

Harvest index measures how much of a plants total photosynthates are translocated into the seed at the end of the growing season (Berti et al., 2011). In wheat (*Triticum aestivum* L.), corn, and soybean harvest index values commonly range from 0.40 to 0.50 (B.L. Johnson, personal communication, 2019). A general range for oilseed crop harvest index is between 0.30 and 0.35, however, harvest index values in oilseed crops typically span a wide range and can be influenced by many events throughout the growing season (Berti et al., 2011). Harvest index values for pennycress typically range between 0.30 and 0.43 (Mason et al., 2012). In camelina, harvest index values often range between 0.17 and 0.27, but can range between 0.10 and 0.40. (Berti et al., 2011; Gesch and Cermak, 2011).

Green cover contribution from volunteer pennycress and camelina

Analysis for percent green cover (PGC) indicated a significant environment by cover crop interaction (Table 8). Percent green cover due to volunteer growth of pennycress and camelina after their respective harvests was measured using the Canopeo © application following soybean harvest in October. The PGC at the Casselton 2018 and Prosper 2017 environments was similar between pennycress and camelina, while at the Prosper 2018 environment PGC provided by pennycress was greater than camelina (Table 17). The 2018 environments had PGC for camelina that was similar, while at the Prosper 2017 environment PGC was 8 and 12% greater than the Casselton and Prosper 2018 environments, respectively. The PGC for pennycress was similar across environments.

Table 17. Mean percent green cover contribution from volunteer pennycress and camelina plants, averaged across three sowing dates at three environments in North Dakota.

	Environment		
	Casselton 2018	Prosper 2017	Prosper 2018
Cover crop			
		%	
Pennycress	5	9	7
Camelina	5	13	1
LSD (0.05)		4	

Measurement taken immediately following soybean harvest

To an extent, this data indicates the potential of both pennycress and camelina to act as self-seeding cover crops in subsequent growing seasons. The degree to which these crops self-seed could vary from year to year and could depend on many factors including, shattering throughout the growing season, timeliness of their harvest or inability to harvest them at all, and how well they thrash in a combine harvester.

The potential for self-seeding of pennycress and camelina if used as intersown cover crops has both benefits and disadvantages. Benefits include potential soil protection following harvest of the primary crop. An additional benefit is the suppression of challenging to control weeds through shading, competition, and potential allelopathy from the presence of pennycress and camelina (Lovett and Jackson, 1980; Gesch and Cermak 2011; Johnson et al., 2015). A disadvantage to pennycress and camelina self-seeding could be potential weed control challenges within a producer's, and surrounding fields. Fortunately many herbicides provide excellent control of pennycress and camelina in a wide array of crops. Tillage is also an effective weed control option, if tillage is part of a producer's management portfolio (McVay and Lamb, 2008; Andersen et al., 2016).

Harvested soybean traits

Statistical analysis across three environments for four soybean traits are shown in Table 18. The design for this analysis is a randomized complete block design consisting of nine intercropping treatments, and one non-treated check (NTC) treatment. Pennycress, camelina, and rye were intersown into soybean at three dates corresponding with soybean growth stages R6, R7, and R8 during the previous growing season. Soybean was then relay-sown into these cover crops during the subsequent growing seasons of 2017 and 2018. The nine intercropping treatments will often be compared with the NTC treatment, in addition to each other.

Table 18. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the combined analyses across three environments of four soybean traits collected in the System-I Year-2 intercropping study conducted in 2017 and 2018 in North Dakota.

		Mean square			
SOV	df	Plant height at harvest	Harvested soybean population	Seed yield	1000-seed weight
Environment	2	3 488	1 247.2	2 086 390	3839.8
Rep (ENV)	9	677	11.6	4 699 184	297.8
Treatment	9	1 633.6**	107.7*	2 650 239**	220.7
ENV × Treatment	18	133.8*	36.5*	514 025 *	196.2**
Error	81	70.9	17.9	257 316	52.3
Total	119				
CV%		13	9.8	21	4.6

*, ** significant at 0.05 and 0.01 level, respectively

Plant height at harvest

Soybean plant height(s) (SPH), measured at the time of soybean harvest indicates the main effect, and the environment by treatment interaction were significant (Table 18). When averaged across environments, SPH was similar for the rye intercropping treatments and the NTC, while SPH for the pennycress and camelina intercropping treatments were less than the NTC (Table 19).

Camelina intercropping treatments reduced SPH when compared with the NTC treatment at the Casselton 2018 environment, while SPH for the pennycress intercropping treatments was similar to the NTC (Table 19). At the Prosper 2017 and 2018 environments, all pennycress and camelina intercropping treatments reduced SPH when compared with the NTC (Table 19).

At the Casselton 2018 environment, all camelina intercropping treatments had a similar SPH. At the Prosper 2017 environment, SPH of the Date 1, 2, and 3 pennycress intercropping treatments were 67.9, 55.9, and 59.1 cm, respectively (Table 19). The Date 1 treatment was similar to Date 3, but higher than Date 2, which was similar to Date 3. The Date 3 treatment had a similar SPH to both Dates 1 and 2. When compared with each other, camelina intercropping treatments at the Prosper 2017 environment had similar SPH. At the Prosper 2018 environment, all pennycress and camelina intercropping treatments had similar SPH (Table 19).

Table 19. Mean soybean plant height of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment			
	Casselton 2018	Prosper 2017	Prosper 2018	Mean
Treatment				
	cm			
Date 1 pennycress	56.5	67.9	69.2	64.6
Date 2 pennycress	55.9	55.9	66.0	59.3
Date 3 pennycress	55.2	59.1	64.8	59.7
Date 1 camelina	52.7	45.7	64.1	54.2
Date 2 camelina	41.3	47.6	67.3	52.1
Date 3 camelina	43.2	43.2	61.6	49.3
Date 1 rye	66.0	82.6	88.9	79.2
Date 2 rye	58.4	81.3	87.0	75.6
Date 3 rye	62.9	75.6	87.0	75.1
Non-treated check (NTC)	64.8	87.0	87.6	79.8
LSD†		11.8		
LSD‡				9.9

Measurement taken at the time of soybean harvest

† LSD to compare the interaction of environment by treatment at the 0.05 level of significance

‡ LSD to compare the main effect of treatment at the 0.05 level of significance

At all environments, SPH of the rye intercropping treatments were similar to the NTC while SPH of all camelina intercropping treatments were less than the NTC (Table 19). At both the Prosper 2017 and 2018 environments SPH of all pennycress intercropping treatments was also less than the NTC (Table 19). These results indicate that rye does not affect SPH when intersown in the previous fall and terminated in the subsequent growing season, prior to the relay-sowing of soybean (Table 1).

Reduced SPH observed in the pennycress and camelina intercropping treatments could be due to intra and interspecific competition for resources (sunlight, water, and space) early in the growing season; coupled with below average rainfall for much of the growing season in both the Prosper 2017 and 2018 environments (Table 7). Other contributing factors to this height reduction could be a result of stress incurred on the soybean plants from mechanical harvest of the pennycress and camelina.

In addition to the previously mentioned stress, SPH and seed yield reductions (discussed later) at the Prosper 2017 environment could be a result of stem cutoff damage from having the cutter bar of the combine harvester below the soybean canopy in an attempt of obtain as much pennycress and camelina seed as possible; which in turn cut off the top nodes of the soybean plants in these treatments. This only occurred at the Prosper 2017 environment. Additionally, across all environments the known allelopathic properties of pennycress and camelina could have partially suppressed growth of the soybean (Patterson, 1981; Vaughn et al., 2006).

Harvested soybean population

Harvested soybean population(s) (HSP) indicates the main effect, and the environment by treatment interaction were significant (Table 18). The main effect of treatment indicated similar HSP in all intercropping treatments compared with the NTC, except for the Date 2 and 3 camelina treatments. These treatments had similar HSP at 38.8 and 38.0 plants m^{-2}, respectively, but were both lower than the NTC (Table 20).

At the Casselton 2018 environment, the NTC had a HSP of 45.2 plants m^{-2}. A similar HSP for all rye intercropping treatments was measured at the Casselton 2018 environment, yet only the Date 1 and 2 treatments had a HSP similar to the NTC with 47.0 and 50.2 plants m^{-2}, respectively (Table 20). The Date 3 treatment had a higher HSP of 52.6 plants m^{-2} compared with the NTC treatment. The Date 1, 2, and 3 pennycress intercropping treatments at the Casselton 2018 environment had similar HSP that were also all similar to the NTC (Table 20). The HSP for the camelina intercropping treatments at this environment were 47.7, 40.6, and 41.9 plants m^{-2} for Dates 1, 2, and 3, respectively (Table 20). Date 1 was higher than Date 2 and similar to Date 3, and Date 2 was only similar to the Date 3 treatment, which was similar to both Dates 1 and 2. All camelina intercropping treatments at this environment were similar to the NTC.

Table 20. Mean harvested soybean populations of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment			
	Casselton 2018	Prosper 2017	Prosper 2018	Mean
Treatment				
	plants m^{-2}			
Date 1 pennycress	42.6	40.3	48.4	43.8
Date 2 pennycress	44.9	37.2	47.0	43.0
Date 3 pennycress	44.9	35.2	48.7	42.9
Date 1 camelina	47.7	31.7	48.7	42.7
Date 2 camelina	40.6	33.9	41.9	38.8
Date 3 camelina	41.9	30.8	41.4	38.0
Date 1 rye	47.0	38.7	48.5	44.7
Date 2 rye	50.2	35.7	52.8	46.2
Date 3 rye	52.6	41.3	46.1	46.7
Non-treated check (NTC)	45.2	44.9	49.5	46.5
LSD†		6.0		
LSD‡				5.2

Measurement taken at the time of soybean harvest

† LSD to compare the interaction of environment by treatment at the 0.05 level of significance

‡ LSD to compare the main effect of treatment at the 0.05 level of significance

At the Prosper 2017 environment, the NTC treatment had a HSP of 44.9 plants m^{-2} (Table 20). The rye intercropping treatments had similar HSP of 38.7, 35.7, and 41.3 plants m^{-2} for Dates 1, 2, and 3, respectively, yet only Date 3 was similar to the NTC (Table 20). The HSP of the Date 1 and 2 rye treatments were less than the NTC. Pennycress intercropping treatments at the Prosper 2017 environment had similar HSP of 40.3, 37.2, and 35.2 plants m^{-2} for Dates 1, 2, and 3, respectively, however only the Date 1 HSP was similar to the NTC (Table 20). The pennycress Date 2 and 3 treatments both had lower HSP in relation to the NTC. The HSP of the camelina intercropping treatments were similar, and lower than the NTC, with 31.7, 33.9, and 30.8 plants m^{-2} for Dates 1, 2, and 3, respectively (Table 20).

At the Prosper 2018 environment, the NTC HSP was 49.5 plants m^{-2} (Table 20). The HSP of the rye intercropping treatments were similar to the NTC at 48.5, 52.8, and 46.1 plants m^{-2} for Dates 1, 2, and 3, respectively (Table 20). Date 1 was similar to both Dates 2 and 3, Date 2 was similar to Date 1 and higher than Date 3, and Date 3 was similar to Date 1 and lower than Date 2. The HSP of the three pennycress intercropping treatments were similar, and were also similar to the NTC (Table 20). Finally, the HSP of the camelina intercropping treatments were 48.7, 41.9, and 41.4 plants m^{-2} for Dates 1, 2, and 3, respectively (Table 20). The HSP of the Date 1 treatment was similar to the NTC, while Dates 2 and 3 were lower. The Date 2 and 3 camelina treatments had similar HSP, yet both were lower than the Date 1 treatment.

Harvested soybean population reductions occurred at both the Prosper 2017 and 2018 environments. At the Casselton 2018 environment, all treatments had similar HSP in relation to the NTC except for the Date 3 rye intercropping treatment, which had a higher HSP (Table 20). This could be due to a higher germination rate, in addition to possible inaccurate scooping of seed into the planter during relay-sowing of that treatment. It should be noted that 100% pure live seed emergence at the desired soybean population of 432,434 pure live seeds ha^{-1} stated in the Materials and Methods section would equate to 43.3 soybean plants m^{-2}. As seen in the table above, several treatments have HSP greater than 43.3 plants m^{-2} (Table 20). Reasons for these high soybean populations in some treatments could be seed germination rates higher than the labeled 90% germination which was used in the soybean sowing rate calculation. This 90% germination is the minimum germination percentage the seed must have for certification (N.J. Steffl, personal communication, 2019). Oftentimes however, seed from reputable sources has germination rates higher than stated on the label. Also, there was potential for both over and under sowing with the scooping method used for metering seed into the planter for each experimental unit area. Additionally, inconsistency in scooping could have resulted from different people scooping, and dumping seed into the planter.

Reductions in soybean seed yield could not be consistently associated with treatments that had reduced HSP at the Prosper 2017 and 2018 environments. Certain treatments that had similar HSP to the NTC also had reduced soybean seed yields (Table 20 and Table 21). At the Prosper 2017 environment, all intercropping treatments except for the Date 1 pennycress and Date 3 rye treatments had lower HSP than the NTC. At the Prosper 2018 environment, only the Date 2 and 3 camelina intercropping treatments had lower HSP than the NTC (Table 20). A contributing factor to the high number of treatments at the Prosper 2017 environment with reduced HSP could be stress on the soybean from the majority of the growing season receiving below average rainfall (Table 7). Additionally, stand reductions could have occurred within the relay-sown soybean in the pennycress and camelina treatments due to stress from stem cutoff damage as a result of having the combine cutter bar below the soybean canopy in an attempt to obtain as much pennycress and camelina seed as possible. This only occurred at the Prosper 2017 environment. Additionally, across all environments the known allelopathic properties of pennycress and camelina could have contributed to HSP reductions within those respective treatments, and merits further investigation in future research (Patterson, 1981; Vaughn et al., 2006).

Seed yield

Soybean seed yield, from now on referred to as soybean yield, or yield, indicated significance for the environment by treatment interaction and the main effect of treatment (Table 18). The main effect of treatment indicated yields similar to the NTC in all rye intercropping treatments and the Date 2 pennycress intercropping treatment (Table 21). The camelina intercropping treatments, along with the Date 1 and 3 pennycress intercropping treatments had lower yields than the NTC.

Table 21. Mean soybean seed yield of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment			
	Casselton 2018	Prosper 2017	Prosper 2018	Mean
Treatment				
	kg ha^{-1}			
Date 1 pennycress	2310	2535	1955	2266
Date 2 pennycress	2888	2388	2161	2479
Date 3 pennycress	2735	2015	1986	2246
Date 1 camelina	2114	1803	1554	1823
Date 2 camelina	1586	1830	2136	1850
Date 3 camelina	2182	1669	1819	1890
Date 1 rye	2727	3475	2665	2956
Date 2 rye	2742	3172	2543	2819
Date 3 rye	3048	3100	2529	2892
Non-treated check (NTC)	2851	3822	2230	2968
LSD†		714		
LSD‡				615

† LSD to compare the interaction of environment by treatment at the 0.05 level of significance

‡ LSD to compare the main effect of treatment at the 0.05 level of significance

At the Casselton 2018 environment, the NTC had a soybean yield of 2851 kg ha^{-1} (Table 21). This soybean yield was similar to the yields obtained from the rye and pennycress intercropping treatments. Soybean yields for the camelina intercropping treatments were similar at 2114, 1586, and 2182 kg ha^{-1} for Dates 1, 2, and 3, respectively (Table 21). Only the soybean yield of the Date 3 treatment was similar to the NTC, however, the soybean yield obtained from both Dates 1 and 2 was lower than the soybean yield obtained from the NTC.

The Prosper 2017 environment had a NTC soybean yield of 3822 kg ha^{-1} (Table 21). Soybean yields for the rye intercropping treatments were similar, and yielded 3475, 3172, and 3100 kg ha^{-1} for Dates 1, 2, and 3, respectively (Table 21). Dates 1 and 2 were similar to the

NTC, whereas the Date 3 treatment yielded 19% less than the NTC. The pennycress intercropping treatments yielded similarly, and were all lower than the NTC with 2535, 2388, and 2015 kg ha^{-1} for Dates 1, 2 and 3, respectively (Table 21). Likewise, the camelina intercropping treatments yielded similarly, and were lower in relation to the NTC at 1803, 1830, and 1669 kg ha^{-1} for Dates 1, 2, and 3, respectively (Table 21). At the Prosper 2018 environment, all intercropping treatments were similar to the 2230 kg ha^{-1} soybean yield obtained from the NTC (Table 21).

These results indicate the presence of an intersown cover crop from the previous fall either has no impact on, or reduces relay-sown soybean yield, compared that of monocropped soybean. Rye had the lowest impact and fewest reductions in soybean yield, while soybean yield reductions in pennycress and camelina treatments had a higher frequency of occurring, and imposed greater yield reductions when they did occur (Table 21). All pennycress, camelina, and the Date 3 rye intercropping treatments experienced yield reductions at the Prosper 2017 environment, while soybean yield reductions only occurred in the Date 1 and 2 camelina intercropping treatments at the Casselton 2018 environment. All intercropping treatments were similar to the NTC at the Prosper 2018 environment (Table 21). The mixed results observed in this study have occurred in other research with pennycress. In a double-crop experiment with pennycress and soybean conducted by Johnson et al. (2015) at three locations in southern Minnesota, two locations experienced no reduction in soybean seed yield, whereas yield reduction occurred at the third location in relation to the monocrop soybean control. Gesch et al. (2014) found relay-sowing soybean into established winter camelina stands from the previous fall consistently reduced soybean seed yield to between 58 and 83% of the monocrop soybean control.

In the System-I Year-2 study, reduced soybean yield observed in certain pennycress and camelina intercropping treatments could be due to intra and interspecific competition for resources (sunlight, water, and space) early in the growing season. An additional contributing factor to this reduced soybean yield could be from stress incurred on the soybean plants from mechanical harvest of the pennycress and camelina. A possible reason for the high number of intercropping treatments with low soybean yields at the Prosper 2017 environment could be below average rainfall for much of the growing season (Table 7). In addition, soybean stem cutoff damage in the pennycress and camelina treatments from having the combine cutter bar below the soybean canopy in an attempt to obtain as much seed from these crops as possible likely reduced soybean yield. This only occurred at the Prosper 2017 environment. Although this cutoff damage may confound soybean yield in these treatments to an extent, this type of damage is quite likely in commercial production, and is one of the many challenges of an intercropping system such as this. Additionally, across all environments the known allelopathic properties of pennycress and camelina could have partially suppressed yield potential of the soybean (Patterson, 1981; Vaughn et al., 2006).

1000-seed weight

Soybean 1000-seed weight, from now on referred to as 1000-seed weight, indicated significance for the environment by treatment interaction in the combined analysis across three environments (Table 18). At the Casselton 2018 environment, the NTC had a 1000-seed weight of 159.9 g (Table 22). The 1000-seed weight of all rye intercropping treatments were similar to the NTC, with 150.7, 157.3, and 169.9 g for Dates 1, 2, and 3, respectively. Dates 1 and 2 had similar 1000-seed weights, however the 1000-seed weight for Date 3 was higher than both Dates 1 and 2. The pennycress intercropping treatments had similar 1000-seed weights that were all higher than the NTC at 173.1, 179.2, and 170.2 g for Dates 1, 2, and 3, respectively (Table 22). The Date 1 camelina intercropping treatment was similar to the NTC 1000-seed weight at 161.4 g. The Date 2 and 3 camelina intercropping treatments were similar, but higher than the NTC and the Date 1 treatment with 1000-seed weights of 176.4 and 174.9 g, respectively (Table 22). Within the Prosper 2017 environment all treatments had similar 1000-seed weights (Table 22).

Table 22. Mean soybean 1000-seed weight of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment		
	Casselton 2018	Prosper 2017	Prosper 2018
Treatment			
		g	
Date 1 pennycress	173.1	142.1	146.1
Date 2 pennycress	179.2	151.9	154.4
Date 3 pennycress	170.2	148.0	157.1
Date 1 camelina	161.4	144.9	153.2
Date 2 camelina	176.4	149.3	165.3
Date 3 camelina	174.9	145.5	168.5
Date 1 rye	150.7	147.3	162.9
Date 2 rye	157.3	146.3	161.0
Date 3 rye	169.9	149.5	158.6
Non-treated check (NTC)	159.9	152.2	147.2
LSD (0.05)		10.2	

The Prosper 2018 environment had a NTC 1000-seed weight of 147.2 g (Table 22). The rye intercropping treatments at this environment had similar 1000-seed weights that were all higher than the NTC at 162.9, 161.0, and 158.6 g for Dates 1, 2, and 3, respectively (Table 22). The 1000-seed weight of the pennycress intercropping treatments were similar to the NTC at 146.1, 154.4, and 157.7 g for Dates 1, 2, and 3, respectively. Date 1 was similar to Date 2 and lower than Date 3, while Dates 2 and 3 were similar (Table 22). The 1000-seed weight for the Date 1 camelina intercropping treatment was similar to the NTC at 153.2 g (Table 22). Camelina Dates 2 and 3 had 1000-seed weights that were similar, and higher than the NTC at 165.3 and

168.5 g, respectively (Table 22). The 1000-seed weight of the Date 1 treatment was less than both the Date 2 and 3 camelina intercropping treatments.

These results indicate that the presence of an intersown cover crop either has no impact on, or increases 1000-seed weight in relay-sown soybean. Phippen and Phippen (2012) found increases in soybean 1000-seed weight following a previous crop of pennycress versus sowing into fallow soil. The increase in 1000-seed weight with the rye treatments at the Prosper 2018 environment could be due to reduced evaporation from the presence of the rye canopy near the soil surface, possibly aiding in enhancing soil water available to the soybean in these treatments throughout the growing season; and ultimately allowing more water resources and associated photosynthesis benefits for allocation to the final yield component, seed weight.

Soil gravimetric water content (GWC)

Statistical analysis across three environments for four soil water traits are shown in Table 23. The design for this analysis is a randomized complete block design consisting of nine intercropping treatments, and one non-treated check (NTC) treatment. Pennycress, camelina, and rye were intersown into soybean at three dates corresponding with soybean growth stages R6, R7, and R8 during the previous growing season. Soybean was then relay-sown into these cover crops during the subsequent growing seasons of 2017 and 2018. Soil water traits for the nine intercropping treatments will often be compared with the NTC treatment, in addition to each other.

Table 23. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the combined analyses across three environments of four soil water traits collected in the System-I Year-2 intercropping study conducted in 2017 and 2018 in North Dakota.

		Mean square			
SOV	df	Post-cover crop harvest GWC (0-30 cm)	Post-cover crop harvest GWC (30-60 cm)	Post-soybean harvest GWC (0-30 cm)	Post-soybean harvest GWC (30-60 cm)
Environment	2	60 095	71 657	122 201	118 705.6
Rep (ENV)	9	1 333.4	2 717.2	480.8	2 581.8
Treatment	9	189.3	339.2	179.8	171
ENV × Treatment	18	508.6**	732.9**	220.8	405.7
Error	81	155.6	308.7	135.5	347.5
Total	119				
CV%		5.1	6.8	4.2	6.3

*, ** significant at 0.05 and 0.01 level, respectively

Post-cover crop harvest GWC (0-30 cm)

Soil GWC taken immediately after cover crop harvest indicated significance for the environment by treatment interaction at the soil profile depth of 0-30 cm (Table 23). At the Casselton 2018 environment, the NTC soil GWC was 291.4 g kg^{-1} (Table 24). The rye, pennycress, and camelina intercropping treatments at this environment were similar within their respective crops and all treatments were similar to the NTC (Table 24). The soil GWC of the Casselton 2018 environment was higher than both Prosper environments for all treatments. Reasons for this could be higher and more frequent rainfall than what occurred at the Prosper environments, and a soil type with slower internal drainage, higher water table, and higher water holding capacity than at Prosper (Table 7) (Soil Survey Staff, 2005; Soil Survey Staff, 2014; Soil Survey Staff, 2016).

Table 24. Mean post-cover crop harvest soil GWC at a profile depth of 0-30 cm of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment		
	Casselton 2018	Prosper 2017	Prosper 2018
Treatment			
		g kg^{-1}	
Date 1 pennycress	300.9	233.1	207.8
Date 2 pennycress	293.6	235.7	210.9
Date 3 pennycress	295.2	226.1	203.5
Date 1 camelina	292.1	229.8	219.6
Date 2 camelina	281.8	227.5	220.9
Date 3 camelina	276.1	230.4	230.1
Date 1 rye	273.8	206.8	228.7
Date 2 rye	290.9	210.0	226.6
Date 3 rye	290.9	203.6	224.7
Non-treated check (NTC)	291.4	231.6	224.8
LSD (0.05)		17.6	

Soil cores extracted immediately after cover crop harvest

At the Prosper 2017 environment, the NTC had a soil GWC of 231.6 g kg^{-1} (Table 24). The soil GWC of the rye intercropping treatments were similar, but less than the NTC at 206.8, 210.0, and 203.6 g kg^{-1} for Dates 1, 2, and 3, respectively (Table 24). All pennycress and camelina intercropping treatments at this environment had a similar GWC, and were similar to the NTC (Table 24). Soil GWC of the NTC treatment at the Prosper 2018 environment was 224.8 g kg^{-1} (Table 24). The soil GWC of the rye, pennycress, and camelina intercropping treatments at this environment were similar within their respective crop, and all treatments were similar to the NTC (Table 24).

In two of the three environments where this experiment was conducted (Casselton 2018 and Prosper 2018), all intercropping treatments had a soil GWC similar to their respective NTC. The Prosper 2017 environment indicated differences in soil GWC from the NTC only for the rye intercropping treatments, which were lower than the NTC (Table 24). In similar research Gesch and Johnson (2015) concluded that in a cropping system where soybean was relay-sown into established camelina water use increased in comparison with water use of a monocrop soybean system. However, this increased demand for soil water from camelina occurs at a time when soybean plants are early in their vegetative stages and demand little soil water. Additionally, this increased soil water demand is often mitigated by excess soil water, or timely rainfall early in the growing season. This increased soil water demand also ceases once physiological maturity of the camelina is reached in approximately mid-to late-June, after which soybean becomes the sole water user (Gesch and Johnson, 2015).

Other research has shown that in years of normal rainfall negligible soil GWC differences result from relay-sown soybean into a rye cover crop versus a soybean monocrop system (De Bruin et al., 2005). This same research study also indicated that years with below normal rainfall can result in significant soil GWC differences between these two cropping systems. At the Prosper 2017 environment, rainfall was below normal from the months of May through August, and could likely be a reason for this difference in soil GWC (Table 7). It has been shown that continuously using rye as a cover crop can enhance the overall water storage capacity of soil, in addition to providing a higher amount of plant available water throughout the growing season (Basche et al., 2016).

Post-cover crop harvest GWC (30-60 cm)

Soil GWC taken immediately after cover crop harvest indicated significance for the environment by treatment interaction at the soil profile depth of 30-60 cm (Table 23). The Casselton 2018 environment exhibited the highest soil GWC among the three environments, and indicated no significant differences among treatments (Table 25). Possible reasons for a higher GWC at this environment are mentioned in the previous section discussing soil GWC at the soil profile depth of 0-30 cm.

Table 25. Mean post-cover crop harvest soil GWC at a profile depth of 30-60 cm of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment		
Treatment	Casselton 2018	Prosper 2017	Prosper 2018
		$g\ kg^{-1}$	
Date 1 pennycress	308.7	266.0	208.8
Date 2 pennycress	315.0	241.7	222.1
Date 3 pennycress	313.7	227.7	207.3
Date 1 camelina	299.9	257.2	218.2
Date 2 camelina	301.9	239.5	227.8
Date 3 camelina	303.7	248.9	221.6
Date 1 rye	296.6	229.0	244.9
Date 2 rye	318.6	237.1	241.3
Date 3 rye	306.4	236.1	249.5
Non-treated check (NTC)	316.0	241.4	247.3
LSD (0.05)		24.7	

Soil cores extracted immediately after cover crop harvest

At the Prosper 2017 environment, the NTC had a soil GWC of 241.4 g kg^{-1} (Table 25). All rye intercropping treatments had a similar soil GWC that was also similar to the NTC (Table 25). Soil GWC of all pennycress intercropping treatments was similar to the NTC with 266.0, 241.7, and 227.7 g kg^{-1} measured for Dates 1, 2, and 3, respectively (Table 25). Date 1 was similar to Date 2 but higher than Date 3, Date 2 was similar to both Dates 1 and 3, and Date 3 was similar to Date 2, but lower than Date 1. All camelina intercropping treatments had a similar soil GWC that was also similar to the NTC.

At the Prosper 2018 environment, the NTC soil GWC was 247.3 g kg^{-1}. All rye intercropping treatments had a similar soil GWC that was also similar to the NTC. The pennycress intercropping treatments had similar soil GWC that was lower than the NTC at 208.8, 222.1, and 207.3 g kg^{-1} for Dates 1, 2, and 3, respectively. (Table 25). Soil GWC of the camelina intercropping treatments at the Prosper 2018 environment were similar, however only the Date 2 treatment soil GWC was similar to the NTC at 227.8 g kg^{-1}. Dates 1 and 3 were lower than the NTC at 218.2 and 221.6 g kg^{-1}, respectively.

All of the intercropping treatments at both the Casselton 2018 and Prosper 2017 environments had soil GWC similar to their respective NTC at the 30-60 cm profile depth. At the Prosper 2018 environment, however, the pennycress and Date 1 and 3 camelina intercropping treatments had soil GWC less than the NTC. These GWC differences are not likely due to water uptake by the pennycress and camelina since both crops are shallow rooted with low water demand. Gesch and Johnson (2015) determined that in camelina 82% of the root density was present in the top 30 cm of soil, while only 12% was present at the deeper profile depth of 30-60 cm. Additionally, at all environments the pennycress and camelina intercropping treatments had similar GWC to the NTC at the 0-30 cm profile depth. It is likely that these GWC differences could have resulted from a growing season with less than average rainfall during the months of May through July (Table 7).

Corn-soybean-corn crop sequence (System-II, Year-2)

Intersown pennycress traits

Statistical analysis across three environments for nine cover crop traits, in addition to soybean plant height and growth stage at cover crop harvest are shown in Table 26. The design for this analysis, due to camelina data not obtained in either of the 2018 environments, is a three treatment randomized complete block design consisting of three pennycress intercropping treatments. Pennycress was intersown into corn at three dates corresponding with corn growth stages R4, R5, and R6 during the previous growing season. Pennycress then established, overwintered, and resumed growth in the subsequent growing seasons of 2017 and 2018. This discussion pertains to trait responses after overwintering and breaking spring dormancy.

Table 26. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the combined analyses across three environments of nine intersown pennycress traits, in addition to soybean plant height and growth stage at cover crop harvest, collected in the System-II Year-2 intercropping study conducted in 2017 and 2018 in North Dakota.

		Mean square										
SOV	df	Flowering date	Cover crop plant height at harvest	Soybean plant height at cover crop harvest	Soybean growth stage at cover crop harvest	Shattering	Lodging	Post-harvest plants m^{-2}	Seed water	Seed yield	Harvest Index†	Volunteer green cover contribution
Environment	2	1 121.40	510.2	3 833.0	148.03	3 402.8	2.30	73 299	75 930	469 409	0.0025	139.1
Rep (ENV)	9	3.95	43.4	52.3	0.20	260.5	0.26	5 030	2 544	31 892	0.0017	42.5
Treatment	2	43.50	19.4	23.8	0.75	40.4	0.25	2 653	1 942	3 653	0.00025	15.3
ENV × Treatment	4	50.20**	19.1	10.9	0.83	45.6	0.21	977	330	102 839	0.00830*	11.1
Error	18	0.79	18.7	21.0	0.51	36.9	0.15	1 624	1 778	35 349	0.0015	67.8
Total	35											
CV%		1.7	10.5	16.5	17.84	35	33	22.7	17.9	32.7	16	105

*, ** significant at 0.05 and 0.01 level, respectively

† Two environments of data were collected for the trait, harvest index, rather than three

Flowering date

Analysis across environments indicated the environment by treatment interaction significant for pennycress flowering date (Table 26). Flowering date (days after 1 April) was similar for all pennycress intercropping treatments at the Casselton 2018 and Prosper 2018 environments (Table 27). At the Prosper 2017 environment, pennycress Dates 1 and 2 had flowering dates 10.2 and 10.5 days earlier, respectively, than pennycress Date 3. Pennycress flowering dates at the Casselton 2018 environment were 2.8, 2.7, and 2.5 days earlier for Dates 1, 2, and 3, respectively than at the Prosper 2018 environment. Additionally, pennycress flowering dates were 21.5, 21.5, and 10.8 days earlier for Dates 1, 2, and 3, respectively, at the Prosper 2017 environment compared with the Prosper 2018 environment, and 18.7, 18.8, and 8.3 days earlier for Dates 1, 2, and 3, respectively, at the Prosper 2017 environment compared with the Casselton 2018 environment; indicating a magnitude interaction response (Table 27). Canola growing degree accumulations on 1 May in 2017 and 2018 were 234 and 120, respectively, and are associated with fewer days to flowering for pennycress at the Prosper 2017 environment due to warmer temperatures in 2017 than 2018 (NDAWN, 2019).

Table 27. Mean calendar days required for three pennycress intercropping treatments to reach 50% flowering at three environments in North Dakota.

	Environment		
Treatment	Casselton 2018	Prosper 2017	Prosper 2018
		calendar days after 1 April	
Date 1 pennycress	56.5	37.8	59.3
Date 2 pennycress	56.3	37.5	59.0
Date 3 pennycress	56.3	48.0	58.8
LSD (0.05)		1.3	

Harvest index

Harvest index of pennycress was determined at the Prosper 2017 and 2018 environments and analysis indicated a significant environment by treatment interaction (Table 26). Harvest index of Dates 1 and 2, and Dates 2 and 3 were similar at the Prosper 2017 environment, however Date 3 had a harvest index 0.07 greater than Date 1 (Table 28). At the Prosper 2018 environment, all pennycress intercropping treatments had a similar harvest index. Significance between environments only occurred for the Date 3 pennycress intercropping treatment.

Table 28. Mean harvest index of three pennycress intercropping treatments at two environments in North Dakota.

	Environment	
	Prosper 2017	Prosper 2018
Treatment		
Date 1 pennycress	0.22	0.25
Date 2 pennycress	0.24	0.25
Date 3 pennycress	0.29	0.19
LSD (0.05)	0.06	

A general range for oilseed crop harvest index is between 0.30 and 0.35, however, harvest index values in oilseed crops typically span a wide range and can be influenced by many events throughout the growing season (Berti et al., 2011). Harvest index values for pennycress typically range between 0.30 and 0.43 (Mason et al., 2012).

Intersown camelina traits from the Prosper 2017 environment

Statistical analysis of eight cover crop traits, in addition to soybean plant height and growth stage at cover crop harvest for the individual environment of Prosper 2017, due to camelina data not obtained in either of the 2018 environments, are shown in Table 29. The design for this analysis is a three treatment randomized complete block design consisting of three camelina intercropping treatments. Camelina was intersown into corn at three dates corresponding with corn growth stages R4, R5, and R6 during the previous growing season. Camelina then established, overwintered, and resumed growth in the subsequent growing season of 2017. This discussion pertain to trait responses after overwintering and breaking spring dormancy.

Table 29. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the individual environment analyses of eight intersown cover crop traits, in addition to soybean plant height and growth stage at cover crop harvest, collected in the System-II Year-2 intercropping study conducted in 2017 at Prosper, North Dakota.

		Mean square									
SOV	df	Flowering date	Cover crop plant height at harvest	Soybean plant height at cover crop harvest	Soybean growth stage at cover crop harvest	Shattering	Lodging	Post-harvest plants m^{-2}	Seed yield	Harvest index	Volunteer green cover contribution
Rep	3	6.6	47.3	139.1	0.55	7.4	7.4	207.4	3 653	0.002	2.9
Treatment	2	6.3	55.4	248.9	0.58	5.1	16.8*	1 111.0	71 196**	0.020*	10.2
Error	6	15.2	119.9	82.6	2.13	8.2	3.1	250.3	6 418	0.003	3.6
Total	11										
CV%		8.1	22.3	21.9	28.3	245.4	33.4	118	90.3	45	121.9

*, ** significant at 0.05 and 0.01 level, respectively

Seed yield

Seed yield differences occurred among camelina intercropping treatments at the Prosper 2017 environment (Table 29). Dates 1 and 2 had similar yields of 9 and 15 kg ha^{-1}, respectively, while the Date 3 intercropping treatment had a higher yield of 243 kg ha^{-1} (Table 30). These yields are all low, and can be attributed to below average rainfall throughout the growing season, and poor stand establishment (Table 7).

Spring camelina stands for Dates 1, 2, and 3, respectively were 25, 47, and 126 plants m^{-2} due to poor initial stand establishment and overwintering (data not shown), with severe mortality occurring from the time camelina treatments exited dormancy until harvest occurred. This in season mortality could have occurred due to unavoidable damage from disruption by the planter units and tractor wheels during relay-sowing of the soybean, and also intra and interspecific competition for resources (sunlight, water, and space). Additionally, self-thinning of camelina could have occurred in these treatments. Though no research is published regarding self-thinning in camelina specifically, it is known that self-thinning occurs in other Brassicaceae family crops such as canola. (Van Deynze et al., 1992). The resultant post-harvest stands of Dates 1, 2, and 3 were 3, 5, and 33 plants m^{-2}, respectively (data not shown).

Table 30. Mean seed yield of three camelina intercropping treatments at the Prosper 2017 environment.

	Treatment		
	Date 1 camelina	Date 2 camelina	Date 3 camelina
		kg ha^{-1}	
	9	15	243
LSD (0.05)		139	

In a cropping sequence where soybean was relayed into fall sown camelina, Berti et al. (2015) reported camelina seed yield at Prosper and Carrington, ND, and Morris, MN. Yields at the Prosper and Carrington, ND locations were averaged across the two years (2012 and 2013) in which the study was conducted, while camelina seed yields at Morris, MN were reported by individual year due to lack of trait variance homogeneity. At Prosper and Carrington, ND the average camelina yield was 1484, and 775 kg ha^{-1}, respectively. Camelina yields for Morris in 2012 and 2013 were 334 and 1932 kg ha^{-1}, respectively. In a different study conducted by Gesch et al. (2014) using the same cropping sequence, consistent camelina seed yields of between 1100 and 1300 kg ha^{-1} were produced over the two years the study was conducted. Harvested stand counts of camelina in the first and second year of the study were 219 and 214 plants m^{-2}, respectively.

Harvest index

Harvest index differences were observed for the camelina intercropping treatments at the Prosper 2017 environment (Table 29). The treatment response was similar as for camelina seed yield at this environment, where camelina Dates 1 and 2 had similar harvest indices of 0.09 and 0.06, respectively, and harvest index for the Date 3 treatment was higher at 0.20 (Table 31). A general range for oilseed crop harvest index is between 0.30 and 0.35, however, harvest index values in oilseed crops typically span a wide range and can be influenced by many events throughout the growing season (Berti et al., 2011). In camelina, harvest index values often range between 0.17 and 0.27, but can range between 0.10 and 0.40. (Berti et al., 2011; Gesch and Cermak, 2011). Harvest index values for camelina Dates 1 and 2 in this experiment were quite low, while the harvest index of Date 3 is a more expected value for camelina (Table 31).

Table 31. Mean harvest index of three camelina intercropping treatments at the Prosper 2017 environment.

	Treatment		
	Date 1 camelina	Date 2 camelina	Date 3 camelina
	0.09	0.06	0.20
LSD (0.05)		0.09	

Harvested soybean traits

Statistical analysis across three environments for four soybean traits are shown in Table 32. The design for this analysis is a randomized complete block design consisting of nine intercropping treatments, and one non-treated check (NTC) treatment. Pennycress, camelina, and rye were intersown into corn at three dates corresponding with corn growth stages R4, R5, and R6 during the previous growing season. Soybean was then relay-sown into these cover crops during the subsequent growing seasons of 2017 and 2018. The nine intercropping treatments will often be compared with the NTC treatment, in addition to each other.

Table 32. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the combined analyses across three environments of four soybean traits collected in the System-II Year-2 intercropping study conducted in 2017 and 2018 in North Dakota.

		Mean square			
SOV	df	Plant height at harvest	Plants m^{-2}	Seed yield	1000-seed weight
Environment	2	11 009	1 226.9	6 209 755	8 515.6
Rep (ENV)	9	110.5	25.4	1 486 453	123.7
Treatment	9	1 477.8**	72.8	2 824 146**	388.3
ENV × Treatment	18	366.5**	33.6	696 294**	659.2**
Error	81	65.48	21.6	273 319	66.7
Total	119				
CV%		11.2	10.8	19.1	5.1

*, ** significant at 0.05 and 0.01 level, respectively

<u>*Plant height at harvest*</u>

Soybean plant height(s) (SPH), measured at the time of soybean harvest indicates the main effect, and the environment by treatment interaction were significant (Table 32). When averaged across environments SPH of the rye and camelina intercropping treatments was similar to the NTC, while the pennycress intercropping treatments had SPH lower than the NTC (Table 33).

At the Casselton 2018 environment, the NTC had a SPH of 67.9 cm (Table 33). The rye and camelina intercropping treatments had similar SPH that were also similar to the NTC. The

SPH of the pennycress intercropping treatments were similar, but less than the NTC, with Dates 1, 2, and 3 having SPH of 41.9, 38.7, and 38.1 cm, respectively (Table 33).

Table 33. Mean soybean plant heights of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment			
Treatment	Casselton 2018 §	Prosper 2017	Prosper 2018 §	Mean
	cm			
Date 1 pennycress	41.9	59.7	83.2	61.6
Date 2 pennycress	38.1	58.4	80.6	59.0
Date 3 pennycress	38.7	55.2	69.9	54.6
Date 1 camelina	66.0	51.4	91.4	69.6
Date 2 camelina	64.8	55.9	97.2	72.6
Date 3 camelina	66.7	50.2	96.5	71.1
Date 1 rye	66.0	89.5	96.5	84.0
Date 2 rye	59.1	85.7	97.8	80.9
Date 3 rye	70.5	87.0	97.2	84.9
Non-treated check (NTC)	67.9	88.9	94.0	83.6
LSD†		11.4		
LSD‡				16.4

Measurement taken at the time of soybean harvest
† LSD to compare the interaction of environment by treatment at the 0.05 level of significance
‡ LSD to compare the main effect of treatment at the 0.05 level of significance
§ Harvest of camelina seed did not occur at this environment

The Prosper 2017 environment had a NTC SPH of 88.9 cm (Table 33). The SPH of the rye intercropping treatments were similar, and were also similar to the NTC. Soybean plant height of the pennycress and camelina intercropping treatments were similar, but less than the NTC. Soybean plant height of the Date 1, 2, and 3 pennycress intercropping treatments were 59.7, 58.4, and 55.2 cm, respectively (Table 33). Camelina intercropping treatments at this environment had soybean plant heights of 51.4, 55.9, and 50.2 cm for Dates 1, 2, and 3, respectively (Table 33).

Soybean plant height of the NTC at the Prosper 2018 environment was 94.0 cm (Table 33). Soybean plant heights of the rye and camelina intercropping treatments were similar, and were also similar to the NTC. The pennycress intercropping treatments had SPH of 83.2, 80.6, and 69.9 cm for Dates 1, 2, and 3, respectively (Table 33). Only the Date 1 treatment had a SPH similar to the NTC. Plant height for Dates 2 and 3 were both shorter than the NTC. When compared amongst each other the Date 1 pennycress intercropping treatment had a SPH similar to the Date 2 treatment, but greater than the Date 3 treatment; while the SPH of the Date 2 and 3 pennycress intercropping treatments were similar.

At all environments, SPH of the rye intercropping treatments was similar to the NTC. At both the Casselton and Prosper 2018 environments the SPH of all camelina intercropping treatments was similar to the NTC, while at the Prosper 2017 environment they were less than the NTC (Table 33). The SPH of the pennycress intercropping treatments was less than the NTC at both the Casselton 2018 and Prosper 2017 environments, while at the Prosper 2018 environment the SPH for these treatments were mixed, with the Date 1 treatment similar to the NTC, and Dates 2 and 3 less than the NTC (Table 33).

These results indicate that rye does not affect SPH when intersown in the previous fall and desiccated prior to the relay-sowing of soybean. The mixed SPH of the pennycress and camelina intercropping treatments across environments, some similar to their respective NTC, and others shorter, indicate the potential for these intersown cover crops to reduce SPH. The potential for SPH reduction could be related to intra and interspecific competition for resources (sunlight, water, and space) early in the growing season; coupled with below average rainfall for much of the growing season at both the Prosper 2017 and 2018 environments (Table 7). Other contributing factors to height reduction could be a result of stress incurred on the soybean plants from mechanical harvest of the pennycress and camelina. In addition to the previously mentioned stress, soybean plant height reductions at the Prosper 2017 environment could be a result of stem cutoff damage from having the combine cutter bar below the soybean canopy in an attempt of obtain as much pennycress and camelina seed as possible; which in turn cut off the top nodes of the soybean plants in these treatments. This only occurred at the Prosper 2017 environment. Additionally, across all environments the known allelopathic properties of pennycress and camelina could have partially suppressed growth of the soybean (Patterson, 1981; Vaughn et al., 2006).

Seed yield

Soybean seed yield, from now on referred to as soybean yield, or yield, indicated significance for the environment by treatment interaction and the main effect of treatment (Table 32). The main effect of treatment indicated similar soybean yields to the NTC for all rye intercropping treatments and the Date 2 and 3 camelina intercropping treatments. All pennycress intercropping treatments and the Date 1 camelina intercropping treatment had lower yields than the NTC (Table 34).

At the Casselton 2018 environment, the NTC had a soybean yield of 2874 kg ha^{-1} (Table 34). Rye intercropping treatments had soybean yields of 2695, 1984, and 2800 kg ha^{-1} for Dates 1, 2, and 3 respectively (Table 34). Yields of Dates 1 and 3 were similar to the NTC while the yield of Date 2 was lower than the NTC. The Date 1 treatment had a yield similar to both Dates 2 and 3, while soybean yield of the Date 2 treatment was similar only to Date 1, and lower than Date 3. Soybean yields of the pennycress intercropping treatments were similar, but lower than the NTC with Dates 1, 2, and 3 producing 1776, 1790, and 1307 kg ha^{-1}, respectively (Table 34). The camelina intercropping treatments had similar soybean yields that were also similar to the NTC (Table 34).

Table 34. Mean soybean seed yield of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment			
Treatment	Casselton 2018 §	Prosper 2017	Prosper 2018 §	Mean
	kg ha^{-1}			
Date 1 pennycress	1776	2336	2625	2245
Date 2 pennycress	1790	2641	2552	2328
Date 3 pennycress	1307	1804	2620	1911
Date 1 camelina	2226	2204	3046	2492
Date 2 camelina	2661	2676	3225	2853
Date 3 camelina	2756	2299	3402	2819
Date 1 rye	2695	3664	3132	3164
Date 2 rye	1984	3657	3020	2887
Date 3 rye	2800	3877	3346	3341
Non-treated check (NTC)	2874	4063	3115	3350
LSD†		736		
LSD‡				716

† LSD to compare the interaction of environment by treatment at the 0.05 level of significance

‡ LSD to compare the main effect of treatment at the 0.05 level of significance

§ Harvest of camelina seed did not occur at this environment

The NTC at the Prosper 2017 environment had a soybean yield of 4063 kg ha^{-1} (Table 34). Soybean yields of the rye intercropping treatments were similar, and similar to the NTC. All pennycress and camelina intercropping treatments had soybean yields less than the NTC. Pennycress Dates 1, 2, and 3 yielded 2336, 2641, and 1804 kg ha^{-1}, respectively (Table 34). The Date 1 treatment was similar to both Dates 2 and 3, while the Date 2 treatment was similar to Date 1 and higher than the yield obtained from the Date 3 treatment. Soybean yields from the camelina intercropping treatments were similar, and yielded 2204, 2676, and 2299 kg ha^{-1} for Dates 1, 2, and 3, respectively (Table 34).

The NTC at the Prosper 2018 environment had a soybean yield of 3115 kg ha^{-1} (Table 34). Soybean yields of the rye, pennycress, and camelina intercropping treatments at this environment were similar to each other within each respective crop and all intercropping treatments were similar to the NTC (Table 34).

These results indicate the presence of an intersown cover crop from the previous fall either has no impact, or reduces soybean yield. Rye had the fewest reductions in soybean yield, followed by camelina; while soybean yield reductions in the pennycress intercropping treatments had the highest frequency of occurring (Table 34). All pennycress and camelina intercropping treatments experienced yield reductions at the Prosper 2017 environment, while soybean yield reductions only occurred in the pennycress and Date 2 rye intercropping treatments at the Casselton 2018 environment. All intercropping treatments were similar to the NTC at the Prosper 2018 environment (Table 34). The mixed results observed in this study have occurred in other research with pennycress. In a double-crop experiment with pennycress and soybean conducted by Johnson et al. (2015) at three locations in southern Minnesota, two locations experienced no reduction in soybean seed yield, whereas yield loss occurred at the third location in comparison to the monocrop soybean control. Gesch et al. (2014) found relay-sowing soybean into established winter camelina stands from the previous fall consistently reduced soybean seed yield to between 58 and 83% of the of the monocrop soybean control.

The reduced soybean yield observed in certain pennycress and camelina intercropping treatments, specifically, could be due to intra and interspecific competition for resources (sunlight, water, and space) early in the growing season. An additional contributing factor to this reduced soybean yield could be from stress incurred on the soybean plants from mechanical harvest of the pennycress and camelina. A possible reason for the high number of intercropping treatments with low soybean yields at the Prosper 2017 environment could be below average rainfall for much of the growing season (Table 7). In addition, soybean stem cutoff damage in the pennycress and camelina treatments from having the combine cutter bar below the soybean canopy in an attempt to obtain as much seed from these crops as possible likely reduced soybean yield. This only occurred at the Prosper 2017 environment. Although this cutoff damage may confound soybean yield in these treatments to an extent, this type of damage is quite likely in commercial production, and is one of the many challenges of an intercropping system such as this. Additionally, across all environments the known allelopathic properties of pennycress and camelina could have partially suppressed yield potential of the soybean (Patterson, 1981; Vaughn et al., 2006).

<u>1000-seed weight</u>

Soybean 1000-seed weight, from now on referred to as 1000-seed weight, indicated significance for the environment by treatment interaction in the combined analysis across three environments (Table 32). At the Casselton 2018 environment, the NTC had a 1000-seed weight of 144.9 g (Table 35). The rye intercropping treatments had 1000-seed weights of 133.9, 125.3, and 137.6 g for Dates 1, 2, and 3 respectively (Table 35). Dates 1 and 3 were similar to the NTC while the Date 2 treatment had a lower 1000-seed weight than the NTC. Date 1 was similar to both Dates 2 and 3, while the Date 2 treatment was similar to Date 1, and lower than Date 3.

Table 35. Mean soybean 1000-seed weight of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment		
Treatment	Casselton 2018 †	Prosper 2017	Prosper 2018 †
		g	
Date 1 pennycress	183.3	151.8	172.7
Date 2 pennycress	173.0	146.1	173.8
Date 3 pennycress	177.3	146.3	176.2
Date 1 camelina	140.1	148.7	175.7
Date 2 camelina	142.0	145.1	179.4
Date 3 camelina	153.9	144.2	180.1
Date 1 rye	133.9	154.6	176.2
Date 2 rye	125.3	155.0	176.3
Date 3 rye	137.6	156.1	176.3
Non-treated check (NTC)	144.9	154.6	172.8
LSD (0.05)		11.5	

† Harvest of camelina seed did not occur at this environment

Pennycress intercropping treatments at the Casselton 2018 environment had 1000-seed weights of 183.3, 173.0, and 177.3 g for Dates 1, 2, and 3, respectively (Table 35). The 1000-seed weight of these treatments were similar, and higher than the 1000-seed weight of the NTC. Phippen and Phippen (2012) also found increases in soybean 1000-seed weight following a previous crop of pennycress versus sowing into fallow soil. Camelina intercropping treatments had similar 1000-seed weights to the NTC at 140.1, 142.0, and 153.9 g for Dates 1, 2, and 3, respectively (Table 35). Date 3 had a greater 1000-seed weight than both Dates 1 and 2, which had similar 1000-seed weights.

The NTC at the Prosper 2017 environment had a 1000-seed weight of 154.6 g (Table 35). The 1000-seed weight of the rye, pennycress, and camelina intercropping treatments at this environment were similar within each respective crop, and all treatments were similar to the NTC (Table 35). At the Prosper 2018 environment, all treatments were similar to the 172.8 g 1000-seed weight obtained for the NTC (Table 35).

Soil gravimetric water content (GWC)

Statistical analysis across three environments for four soil water traits are shown in Table 36. The design for this analysis is a randomized complete block design consisting of nine intercropping treatments, and one non-treated check (NTC) treatment. Pennycress, camelina, and rye were intersown into corn at three dates corresponding with corn growth stages R4, R5, and R6 during the previous growing season. Soybean was then relay-sown into these cover crops during the subsequent growing seasons of 2017 and 2018. Soil water traits for the nine intercropping treatments will often be compared with the NTC treatment, in addition to each other.

Table 36. Sources of variation (SOV), degrees of freedom (df), and trait mean squares for the combined analyses across three environments of four soil water traits collected in the System-II Year-2 intercropping study conducted in 2017 and 2018 in North Dakota.

		Mean square			
SOV	df	Post-cover crop harvest GWC (0-30 cm)	Post-cover crop harvest GWC (30-60 cm)	Post-soybean harvest GWC (0-30 cm)	Post-soybean harvest GWC (30-60 cm)
Environment	2	11 776.1	55 974	89 218	130 136
Rep (ENV)	9	566.5	3 052.2	329.3	747.3
Treatment	9	216.6	1 065.2	166.9	255.7
ENV X Treatment	18	161.6	1628.5	119.5*	181.8
Error	81	150.3	1 410.4	61.1	275.2
Total	119				
CV%		5.5	15.1	2.9	5.8

*, ** significant at 0.05 and 0.01 level, respectively

Post-soybean harvest GWC (0-30 cm)

Soil GWC taken immediately after soybean harvest indicated significance for the environment by treatment interaction at the soil profile depth of 0-30 cm (Table 36). At the Casselton 2018 environment, the NTC had a soil GWC of 321.5 g kg^{-1} (Table 37). The rye, pennycress, and camelina intercropping treatments at this environment were similar to each other within their respective crops and all treatments were similar to the NTC (Table 37). The Casselton 2018 environment had the highest soil GWC measured in this experiment. Reasons for this could be due to higher and more frequent rainfall than what occurred at the Prosper environments, and a soil type with slower internal drainage, higher water table, and higher water holding capacity than at Prosper (Table 7) (Soil Survey Staff, 2005; Soil Survey Staff, 2014; Soil Survey Staff, 2016).

Table 37. Mean post-soybean harvest soil GWC at a profile depth of 0-30 cm of nine intercropping treatments and a non-treated check at three environments in North Dakota.

	Environment		
Treatment	Casselton 2018 †	Prosper 2017	Prosper 2018 †
	$g\ kg^{-1}$		
Date 1 pennycress	317.0	226.7	255.2
Date 2 pennycress	322.6	234.8	254.1
Date 3 pennycress	326.4	226.7	254.9
Date 1 camelina	326.6	226.2	256.6
Date 2 camelina	321.9	231.6	253.4
Date 3 camelina	323.8	222.5	252.7
Date 1 rye	327.9	250.9	259.2
Date 2 rye	328.9	238.4	246.5
Date 3 rye	322.6	240.0	253.0
Non-treated check (NTC)	321.5	241.2	255.9
LSD (0.05)		11.0	

Soil cores extracted immediately after soybean harvest
† Harvest of camelina seed did not occur at this environment

At the Prosper 2017 environment, the NTC had a soil GWC of 241.2 g kg^{-1} (Table 37). The soil GWC of all rye intercropping treatments was similar to the NTC at 250.9, 238.4, and 240.0 g kg^{-1}, for Dates 1, 2, and 3, respectively (Table 37). Date 1 was similar to Date 3 and greater than Date 2, which was similar to Date 3 and less than Date 1; while Date 3 was similar to both Dates 1 and 2. Pennycress intercropping treatments had a similar soil GWC of 226.7, 234.8, and 226.7 g kg^{-1} for Dates 1, 2, and 3, respectively. Both Dates 1 and 3 had a lower soil GWC than the NTC, while the soil GWC of the Date 2 treatment was similar to the NTC. Likewise, the camelina intercropping treatments had a similar soil GWC of 226.2, 231.6, and 222.5 g kg^{-1} for Dates 1, 2, and 3, respectively (Table 37). Both Dates 1 and 3 had a lower soil GWC than the NTC, while the soil GWC of the Date 2 treatment was similar to the NTC.

At the Prosper 2018 environment, the NTC had a soil GWC of 255.9 g kg^{-1} (Table 37). The rye, pennycress, and camelina intercropping treatments at this environment were similar to each other within their respective crops and all intercropping treatments were similar to the NTC (Table 37).

The different soil GWC among certain intercropping treatments at the Prosper 2017 environment is likely due to the majority of the growing season having below average, and erratic rainfall (Table 7). Rainfall in the months of May through August were consistently below the long-term average. September had above average rainfall when compared with the long-term average, followed by rainfall that was below the long-term average again in October; with soybean harvest at this environment occurring on 19 October. In a two year study conducted by Gesch and Johnson (2015), the total water use of a cropping system where soybean was relay sown into established camelina was 21-and 48-mm greater in the first and second year of the study, respectively, than the 465-and 277-mm of total water used by the soybean monocrop treatment. Although water use was greater in the cropping system where soybean was relay-sown into established camelina, the authors concluded that the additional quantity was small in relation to what was used by the soybean, and would not be detrimental in growing seasons with timely and average rainfall.

SUMMARY/CONCLUSION

As today's producers continue to focus on enhancing soil health, cropping system diversity, land use efficiency, and overall economic sustainability, value-added enterprises are becoming more integral in production agriculture. In eastern North Dakota, the use of cover crops has sparked interest with producers as a way to enhance these factors. One method of using cover crops that has drawn interest from producers is relay-sowing a primary crop, such as soybean, into an established winter annual cover crop that was intersown in the previous fall and harvesting the seed of both crops at different times during the same growing season. Limited research has been done on this type of cropping system, especially in this region. Therefore, it is critical to assess the practicality and feasibility of such a cropping system to provide producers information on what to expect with such a system.

Performance of this type of cropping system was evaluated at Prosper, ND, in 2017 and in Casselton and Prosper, ND, in 2018. Pennycress, camelina, and rye were the intersown cover crops established in the previous growing season, and soybean, the relay-sown primary crop. This cropping system was assessed in two different crop sequences as well, soybean-soybean-corn (System-I), and corn-soybean-corn (System-II). Traits evaluated for the intersown cover crops were flowering date, height at harvest, shattering, lodging, spring and post-harvest plants m^{-2}, in season stand mortality, seed water, seed yield, harvest index, and green cover contribution from volunteers. Traits evaluated for the relay-sown soybean were growth stage at cover crop harvest, plant height at both cover crop harvest and soybean harvest, harvested soybean population, seed yield, and 1000-seed weight. Soil gravimetric water content (GWC) was determined at the 0-30 cm and 30-60 cm depths after cover crop harvest and soybean harvest.

Pennycress consistently flowered earlier than camelina at all environments in System-I. Earlier flowering dates for both crops at the Prosper 2017 environment was due to a greater accumulation of growing degree days early in the season. This was also observed among the pennycress flowering dates in System-II. Substantial mortality occurred in pennycress and camelina stands in System-I between when these crops broke dormancy and were harvested. Pennycress and camelina seed yields were impacted from stand losses associated with this mortality, with the lowest yield for both crops occurring at the Prosper 2017 environment where below average rainfall also affected yield. In System-II, where the winter annual cover crops were intersown into corn rather than soybean, establishment of camelina was more of a challenge than it was in System-I. Slower stand establishment resulted in similar plant heights of camelina and soybean at the time of camelina harvest, and thus prevented mechanical harvest of the camelina at both the Casselton and Prosper 2018 environments.

At the time of soybean harvest in both System-I and System-II, rye as an intersown cover crop did not reduce soybean plant height. Soybean plant height was either similar to or lower than the NTC with pennycress or camelina as an intersown cover crop. Soybean yield in both System-I and System-II was either similar, or less than the NTC with the presence of an intersown cover crop. In System-I rye had the lowest frequency of reducing soybean yield, followed by pennycress, and camelina had the highest frequency. In System-II rye again had the lowest frequency of reducing soybean yield, followed this time by camelina, and pennycress had the highest frequency of reducing soybean yield.

When deciding whether or not to integrate an alternative cropping system such as this into a farming operation, it is of utmost importance to assess whether or not it is financially feasible to do so. For pennycress and camelina annual fixed costs for these cropping systems would include costs associated with seed, fertilizer, aerial intersowing, and harvest which equates to approximately \$50, \$55, \$44, and \$85 ha $^{-1}$, respectively, for a total of \$234 ha $^{-1}$ (Curell, 2012; Mason et al., 2012; Arnason, 2016; Haugen, 2017; Mohammed et al., 2017; Agricultural Resource Marketing Center, 2018; West Central Ag Services, 2019). With the assumption that the commodity value of both pennycress and camelina is similar to that of canola (currently ≈ \$0.33 kg^{-1}), due to very few established markets for pennycress and camelina, and consequently, no available price history; a yield of 709 kg ha $^{-1}$ would need to be obtained with no reduction in soybean yield to render these cropping systems feasible (Gesch et al., 2014; Agricultural Resource Marketing Center, 2018; Ray Farmers Union Elevator, 2019). In both System-I and System-II of this experiment, these thresholds were not obtained. Regarding the use of winter rye as an intersown cover crop, being soybean yields in these treatments were more often than not similar to the NTC, rye could be a feasible intersown cover crop option for producers if they deemed its benefits worth the cost of aerially intersowing and terminating it in the spring (≈ \$77 ha $^{-1}$) (Curell, 2012; Jenks, 2019).

Results from these experiments conclude that relay-cropping soybean into previously intersown, established, pennycress and camelina with the intent to harvest seed from both crops in the same growing season is not a feasible cropping system option in either soybean-soybean-corn or corn-soybean-corn crop sequences. Pennycress and camelina yields produced are not substantial enough to outweigh their input cost, or the potential yield loss that can be experienced in the relay-sown soybean. Additionally, even if yields from these crops were substantial enough to be profitable, available markets for sale of the seed are limited, and nonexistent in the immediate region. Rye could be a viable cover crop option in these crop sequences if the producer deems the benefits more substantial than the additional input cost.

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