

RESEARCH FROM POD TO POD:  
HARVEST OPTIMIZATION OF SHATTER-RESISTANT PENNYCRESS,  
CAMELINA INTEGRATION INTO THE CORN-SOYBEAN ROTATION,  
AND COMMUNICATING SCIENCE VIA PODCAST

A Dissertation

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Julija Alda Cubins

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Samantha Wells, Russ W. Gesch

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## Dedication

To the younger version of myself.

This dream is complete, now onto the next big thing.

## Summary

Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr) dominate the agricultural landscape in the Upper Midwest, but limits crop production to the summer months. There is a fallow period from late autumn through the spring that is associated with externalities such as nutrient loss and a lack of economically-viable crop production despite useable growing degree days during that period. Thus, pennycress (*Thlaspi arvense* L.) and camelina (*Camelina sativa* L.) are crops of interest for use during the corn-soybean fallow period. While both crops have been researched heavily for the past decade, questions about their production remain unanswered. Thus, the purpose of this dissertation is to further understand how pennycress harvest can be optimized for use within the corn-soybean rotation; observe the agronomic and economic dynamics when camelina is integrated into the corn-soybean rotation as a winter cash crop; further describe the effect of camelina in nutrient loss prevention over the typically-fallow period; and assess the role of camelina in the corn-soybean carbon cycle. All agronomic experiments were carried out over the 2019 and 2020 growing seasons. The pennycress experiment was conducted in Rosemount, MN, USA, while the camelina experiments were conducted in Morris and Rosemount, MN, USA. However, the research process does not end after data collection, analysis, and publication. For many scientists, there is a growing need to communicate findings with the general public rather than just to academic peers and industry and government stakeholders. This dissertation also explores the use of podcasting as a science communication medium through an experiential project, Hooked on Science.

## Table of Contents

|   |    |
|---|----|
| List of Tables .....  | v  |
| List of Figures .....   | x  |
| 1. Harvest aids did not advance maturity of non-shatter pennycress.....   | 1  |
| 1.1. Summary .....  | 1  |
| 1.2. Introduction.....  | 2  |
| 1.3. Materials and Methods .....  | 4  |
| Cultural practices.....   | 5  |
| Treatments and data collection .....  | 6  |
| Post-season analyses.....   | 7  |
| Statistical analysis .....  | 8  |
| 1.4. Results and Discussion .....   | 8  |
| Environmental conditions.....   | 8  |
| Phenological development .....  | 9  |
| Seed and biomass moisture .....   | 12 |
| Post-harvest measurements .....   | 15 |
| 1.5. Conclusions.....   | 16 |
| 1.6. Tables and Figures .....   | 18 |
| 2. Agronomic and economic trade-offs of integrating camelina into the corn-soybean<br>rotation .....                  | 25 |
| 2.1. Summary .....  | 25 |
| 2.2. Introduction.....  | 26 |
| 2.3. Materials and Methods .....  | 29 |
| Cultural practices .....  | 29 |
| Experimental design.....  | 30 |
| In-season measurements .....  | 33 |
| Plant analysis .....  | 34 |
| Economic analysis .....   | 34 |
| Statistical analysis.....   | 36 |
| 2.4. Results and Discussion .....   | 38 |
| Environmental conditions .....  | 38 |
| Corn yield.....   | 39 |
| Camelina seed yield .....   | 40 |
| Camelina seed quality .....   | 43 |
| Soybean seed yield.....   | 44 |
| Soybean seed quality.....   | 49 |
| Aggregate seed yield.....   | 50 |
| Cropping system economics .....   | 51 |
| 2.5. Conclusions.....   | 55 |
| 2.6. Tables and Figures .....   | 56 |
| 3. Camelina impact on soil nutrients, carbon dioxide efflux, and soil carbon within<br>the corn-soybean rotation..... | 72 |
| 3.1. Summary .....  | 72 |

|   |     |
|---|-----|
| 3.2. Introduction.....  | 73  |
| 3.3. Materials and Methods .....  | 76  |
| Cultural practices.....   | 76  |
| Agronomic management .....  | 77  |
| In-season measurements.....   | 78  |
| Soil analysis.....  | 79  |
| Statistical analysis .....  | 80  |
| 3.4. Results and Discussion .....   | 80  |
| Environmental conditions.....   | 80  |
| Soil nutrient content .....   | 82  |
| Soil carbon dioxide flux .....  | 88  |
| Soil carbon.....  | 92  |
| 3.5. Conclusions.....   | 93  |
| 3.6. Tables and Figures .....   | 94  |
| <br>  |     |
| 4. Can we get Hooked on Science? The challenges and opportunities of creating and<br>maintaining a science podcast in an academic setting ..... | 100 |
| 4.1. Summary .....  | 100 |
| 4.2. Introduction.....  | 101 |
| 4.3. Hooked on Science: A case study in podcasting .....  | 103 |
| Benefits and opportunities.....   | 104 |
| Challenges .....  | 107 |
| 4.4. Future directions .....  | 110 |
| 4.5. Tables and Figures .....   | 111 |
| <br>  |     |
| References.....   | 93  |

## List of Tables

|  |    |
|--|----|
| Table 1-1. Baseline soil samples of the trial sites for the 2018-2019 and 2019-2020 growing seasons.....   | 19 |
| Table 1-2. Mean monthly air temperature and cumulative precipitation over the 2018-2019 and 2019-2020 growing season and the 30-year normal (1991-2020) for Rosemount, MN experimental site. ....  | 20 |
| Table 1-3. Harvest aid treatments active ingredients and rates and the intended pennycress growth stage at application versus actual growth stage at application during the 2019 and 2020 growing seasons. ....  | 21 |
| Table 1-4. Mixed effects model analysis of variance for in-season and post-harvest parameters by harvest aid treatment. ....   | 22 |
| Table 1-5. Pennycress cumulative growing degree days (GDD) at physiological maturity and mean values for pennycress harvest parameters at harvest maturity over the 2018-2019 and 2019-2020 growing seasons and the overall average for both experimental years..... | 23 |
| Table 2-1. Mean monthly air temperature and cumulative precipitation over the 2019 and 2020 growing seasons and the 30-year normal (1991-2020) for the Morris and Rosemount, MN experimental sites.....  | 57 |
| Table 2-2. Summary of field management practices for corn, camelina, and soybean at Morris and Rosemount, MN over the 2019 and 2020 growing seasons.....   | 58 |
| Table 2-3. Mixed effects model analysis of variance for crop seed yield by corn relative maturity (RM), stover presence (S), and their interaction (RM x S). ....  | 60 |

Table 2-4. Mixed-model analysis of variance of camelina and soybean seed quality by corn relative maturity (RM), stover presence (S), and their interaction (RM x S). .....61

Table 2-5. Mixed effects model analysis of variance for approximate processed value by corn relative maturity (RM), stover presence (S), and their interaction (RM x S). .....62

Table 2-6. Camelina ground cover in the autumn and spring by corn relative maturity, stover presence, and their interaction. Values within a column and treatment type that share a letter are not statistically significant from each other based on Tukey’s HSD ( $P < 0.05$ ). .....63

Table 2-7. Camelina and soybean seed oil content and crude protein by corn relative maturity. Values within a column that share a letter are not statistically significant from each other based on Tukey’s HSD ( $P < 0.05$ ). Values within a column that do not have letters were not significantly different from each other. All values are presented on a dry matter basis. ....64

Table 2-8. The approximate processed value (APV) of corn, camelina, and soybean and net aggregate APV by corn relative maturity, stover presence, and the interaction between the two main effects. Values within a treatment type and column that share a letter are not statistically significant from each other based on Tukey’s HSD ( $P < 0.05$ ). Values within a treatment type and column that do not have letters were not significantly different from each other. ....65

Table 3-1. Mean monthly air temperature and cumulative precipitation over the 2019 and 2020 growing season at the Morris and Rosemount, MN experimental sites. ....95

Table 3-2. Average soil nutrient values taken at depths of 0-30 and 30-60 cm in autumn 2019, spring 2020, and summer 2020. ....96

Table 3-3. Significant soil NO<sub>3</sub><sup>-</sup> within a depth, sampling interval, and treatment. ....97

Table 3-4. Camelina seed and stem and leaf biomass quality by main effect and interaction. Values within an effect and column that share a letter are not statistically significant from each other based on Tukey's HSD (*P* < 0.05). Values within an effect and column that do not have letters were not significant from each other. ....98

Table 4-1. Hooked on Science episodes and length by release date.....112

## List of Figures

|  |    |
|--|----|
| Figure 1-1. Biomass moisture of non-shatter pennycress at harvest maturity over the 2018-2019 and 2019-2020 growing seasons. Treatments that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ).....   | 24 |
| Figure 2-1. Corn yield by corn relative maturity. Relative maturities that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ).....   | 66 |
| Figure 2-2. Camelina yield by corn relative maturity. Relative maturities that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ).....   | 67 |
| Figure 2-3. Camelina yield by stover presence. Relative maturities that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ).....  | 68 |
| Figure 2-4. Soybean yield by the interaction of corn relative maturity and stover presence for the Morris site. Treatments that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ). Soybean control treatments were not statistically significant from each other and were combined for presentation.    | 69 |
| Figure 2-5. Soybean yield by the interaction of corn relative maturity and stover presence for the Rosemount site. Treatments that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ). Soybean control treatments were not statistically significant from each other and were combined for presentation. | 70 |

Figure 2-6. Aggregate seed yield by corn relative maturity. Control plots were split by maturity group (representing the two locations). Treatments that share a letter of significance are not statistically different from each other based on Tukey’s HSD ( $P < 0.05$ ). Corn relative maturity treatments were not significantly different between locations and were combined for presentation. Control treatments were not statistically significant from each other and were combined for presentation. ....71

Figure 3-1. The effect of corn relative maturity treatment by stover presence on soil CO<sub>2</sub> flux by date. Within a date, treatments that share a letter are not statistically significant from each other based on Tukey’s HSD ( $P < 0.05$ ). Values are means  $\pm$  S.E., n = 6. ...99

Figure 4-1. Hooked on Science guest professions by number of guests. ....114

Figure 4-2. Examples of graphics from the Hooked on science brand kit. Logo for distribution platforms (left) and the banner for the Facebook page (right). ....115

Figure 4-3. Hooked on Science plays by state. ....116

# **1. HARVEST AIDS DID NOT ADVANCE MATURITY OF NON-SHATTER PENNYCRESS**

## **1.1. SUMMARY**

Reliance on summer annual crops in the Upper Midwest results in fallow land during the late fall through early spring, providing opportunities to integrate economically-viable winter crops, such as pennycress (*Thlapsi arvense* L.), onto the landscape. Pennycress has primarily been studied in agronomic settings using unimproved wild type lines prone to seed shatter resulting in significant yield loss if not harvested early. However, plant and seed moisture can be high, complicating harvest and seed storage. A new breeding line with a reduced-shatter mutation made it possible to study the use of harvest aids to reduce plant moisture without the risk of seed loss. The objectives of this study were to quantify the reduction in pennycress seed and biomass moisture after applying a harvest aid and to assess the seed yield, oil content, and crude protein of the reduced-shatter line. This study was conducted over the 2018-2019 and 2019-2020 growing seasons with ‘IO217’ pennycress in Rosemount, MN, USA. Seed moisture decreased to a similar level by harvest maturity regardless of treatment while swathing was the most effective method of reducing biomass moisture. Natural senescence decreased pennycress moisture content to a harvestable level at the same rate as treated plants indicating that a harvest aid is not required at this time. Seed oil content and crude protein values averaged 323 and 188 g kg<sup>-1</sup>, respectively, which is comparable to values in prior pennycress research. Seed yield was two-to-six times higher than in studies using unimproved pennycress lines. Challenges associated with wild type pennycress lines, such as uneven germination and late

maturation, were still prevalent in this study and further genetic improvement will be necessary to ensure successful pennycress production in the Upper Midwest.

## **1.2. INTRODUCTION**

Throughout the Upper Midwest, there is an opportunity to increase agricultural productivity and profit without displacing current production. These opportunities are the result of an almost exclusive reliance on summer annual crops in this region. Typically, crops are planted in April or May and harvested in October, which leaves land fallow in the early spring and late fall (Heggenstaller et al., 2008). Despite the norm, crop production can continue throughout this period through the use of temporal intensification (Heaton et al., 2013). Temporal intensification is a practice where a secondary crop is integrated onto the landscape during the fallow shoulder season using land that is already in production during the primary growing season. However, this practice is not widely adopted due to a lack of commercially viable winter annual species (Roesch-McNally et al., 2017; Sindelar et al., 2017). The most common suggestions for winter annual species in the Upper Midwest include winter rye (*Secale cereale* L.), triticale (x *Triticosecale* Wittmack), and barley (*Hordeum vulgare* L.) (University of Minnesota Extension, 2021). While these species can be harvested for a commercially-viable product, they are typically terminated during the vegetative growth phase. Based on this historic use, winter rye, triticale, and barley fill the role of a cover crop rather than a commercial crop meaning that they provide important environmental services to growers but do not yield a product that has a direct economic return. This has resulted in low adoption of winter crops across the Upper

Midwest, where only 1-10% of production land is annually cover cropped, depending on the state and county (Wallander et al., 2021).

Recent advances in the breeding and agronomic management of winter crops may present a solution to this problem. Pennycress is a winter annual oilseed Brassicaceae that can be grown during the typically-fallow period between October and May and results in the harvest of a marketable oil product (Moser, 2012; Cubins et al., 2019). Pennycress is native to Eurasia, but has naturalized to many environments around the world including various growing regions in the United States (Holm et al., 1997; Warwick et al., 2002). Within the Upper Midwest, the pennycress growing season is relatively short and typically corresponds with a September planting date and mid-June harvest date (Dose et al., 2017; Cubins et al., 2022). While this time period somewhat overlaps with the summer annual growing season (i.e., May through September), pennycress production can make up for the reduction in summer annual crop yield that occurs as a result of this shift (Johnson et al., 2015, 2017; Ott et al., 2019). Following harvest, pennycress seed can be pressed for oil and usually contains between 260 and 360 g kg<sup>-1</sup> of oil (Cubins et al., 2019). When compared with other common oilseed species grown in the region [e.g., soybean (*Glycine max* [L.] Merr) and canola (*Brassica napus* L.)], pennycress seed produces a comparable or greater amount of oil per seed (Balbino, 2017). Research on post-harvest markets for pennycress oil has focused primarily on its use as a biofuel feedstock, but more recently, pennycress lines with low erucic acid content have shown promise for edible oil markets as well (Moser et al., 2009; Moser, 2012; Chopra et al., 2020).

Despite its promise, there are questions surrounding the basic agronomic management of pennycress that have yet to be answered. Prior research on pennycress in the Upper Midwest has focused on selected wild type lines (e.g., ‘MN106’ and ‘Beecher’), which retain weedy characteristics that are advantageous to weed seed production, but hinder production in an agricultural setting (Isbell et al., 2015, 2017; Carlson, 2018; Chopra et al., 2020; Cubins et al., 2022). One such characteristic is silicle shatter when plant moisture is low (Carlson, 2018; Chopra et al., 2020; Cubins et al., 2022). Seed shatter is a significant issue in Brassicaceae and it is estimated that pennycress yield losses due to silicle shatter can exceed 25% of the total seed yield (Vera et al., 2007; Sintim et al., 2016; Carlson, 2018; Cubins et al., 2022). To help combat this loss, chemical desiccation and swathing are common practices in Brassicaceae production to reduce plant moisture following physiological maturity (Sanderson, 1976; Kandel and Hanson, 2013; Sintim et al., 2016). By quickly drying and harvesting the crop, it is possible to minimize seed losses associated with decreased plant moisture content. However, the use of shatter-prone lines like ‘MN106’ in agronomic research has made it difficult to understand the role of harvest aids in pennycress production (Cubins, 2019). Recent advancements in pennycress breeding have led to the availability of reduced shatter lines that can be used to better assess the viability of harvest aids (Chopra et al., 2020). Thus, the objectives of this study were to 1) quantify the reduction in pennycress seed and biomass moisture between physiological and harvest maturities after the application of a harvest aid and 2) assess the seed yield, oil content, and crude protein of a reduced-shatter pennycress line.

### **1.3. MATERIALS AND METHODS**

### *Cultural practices*

Field experiments were conducted during the 2018-2019 and 2019-2020 growing seasons at the University of Minnesota Rosemount Research and Outreach Center in Rosemount, MN (44°42'35" N 93°04'18" W). The soil at the Rosemount site was classified as a Waukegan silt loam (fine-silty over sand-skeletal, mixed, superactive, mesic Typic Hapludoll) over both growing seasons. Baseline soil samples were collected prior to pennycress planting on a site-wide basis and analyzed for active acidity, organic matter, total inorganic nitrogen, cation exchange capacity, phosphorous, potassium, calcium, and magnesium (Table 1). Monthly precipitation and mean air temperature were recorded by a weather station at the Rosemount site. The historical 30-year (1991-2020) air temperature and precipitation averages were available for the Rosemount Research and Outreach Center (National Centers for Environmental Information, 2021). The average monthly temperature and cumulative precipitation throughout the study period and the 30-year normal for both parameters are presented in Table 2.

In both years, spring wheat (*Triticum aestivum* L.) preceded pennycress and the field was prepared for seeding using a field cultivator. All plots were planted with 'IO217' pennycress, which has a reduced-shatter mutation (Ta-ind-2) previously described by Chopra et al., 2020. The planting rate was 11.2 kg ha<sup>-1</sup> and the plots were 3.0 m long x 3.0 m wide. In 2018, pennycress was planted on 27 September using a cone planter with 25.4 cm row spacing. In 2019, the pennycress was planted on 15 September using a grain drill with 19 cm row spacing. Fertilizer was broadcast by hand a rate of 79-34-34 kg ha<sup>-1</sup> of N-P-K on 25 April 2019 and 4 May 2020 for each respective growing season following spring thaw.

### *Treatments and data collection*

Plots were arranged in a randomized complete block design with four replications. The experimental treatments were harvest aids applied at or near physiological maturity (Table 3). Physiological maturity was characterized by growth stages 85-86 on the extended BBCH scale for camelina and corroborated by prior pennycress research (Martinelli and Galasso, 2011; Cubins et al., 2022). Chemical harvest aids included Defol 5 (NaClO<sub>3</sub>), which has been previously used as a chemical desiccant on pennycress, and Diquat (C<sub>12</sub>H<sub>12</sub>N<sub>2</sub>Br<sub>2</sub>), which was selected based on its broad use as a chemical desiccant for many agricultural crops including canola (Table 3; Environmental Protection Agency, 2002; Cubins, 2019). Swathing was also investigated as a potential pennycress harvest aid due to its historical use in canola production (Vera et al., 2007; Kandel and Hanson, 2013). Pennycress seed and biomass moisture was characterized at both physiological and harvest maturities to provide a baseline for comparison and to compare harvest aid effectiveness with a naturally-senescing control, respectively. In 2019, treatments were applied on 2 July when pennycress growth stage averaged 85.5 (Table 3). In 2020, treatments were applied on 17 June when pennycress was at an average growth stage of 86.2 (Table 3).

Pennycress reached harvest maturity on 8 July and 24 June in 2019 and 2020, respectively. All plots were hand harvested for seed yield by taking a 0.25 m<sup>2</sup> area from the center of the plot. Harvested plants were bagged and dried at 65°C for 48 h to a constant mass before threshing and screen cleaning seed. This seed was tested for moisture, which was used to adjust the seed yield to a moisture content of 80 g kg<sup>-1</sup>. Seed and biomass moisture at harvest were calculated by taking an additional set of samples for each parameter within the plot outside the seed yield harvest area. Seed was hand threshed from

the silicle and weighed immediately and then again after it was dried at 65°C to a constant mass to determine seed moisture at harvest. Biomass moisture was determined by weighing the samples following harvest and then again after being dried at 65°C to a constant mass.

#### *Post-season analyses*

Seed oil content and crude protein were measured using near infrared spectroscopy (NIRS) with a DA 7250 At-line NIR Instrument with custom calibrations for pennycress (Pertec Instruments, Hägersten, Sweden). Spectra were collected at room temperature using 0.2 g to 5.0 g of pennycress seed with the Micro Mirror Module™ from Pertec Instruments with a 950-1650 nm wavelength range and a scan resolution of 5 nm. The methods to perform NIRS analysis have been described in previous pennycress research (Chopra et al., 2019). Seed oil content and crude protein values were adjusted to a dry matter basis for analysis and presentation using the seed moisture content at the time of NIRS analysis.

Cumulative growing degree days (GDD) (°C d) were retroactively calculated for pennycress using the daily maximum soil temperature ( $T_{max}$ ), daily minimum soil temperature ( $T_{min}$ ), and the established base temperature and ceiling temperature ( $T_b$  and  $T_c$ , respectively) (Eq. 1).

$$Cumulative\ GDD = \sum \left( \frac{T_{max} + T_{min}}{2} \right) - T_b \quad (1)$$

The  $T_b$  and  $T_c$  for pennycress are -2.5°C and 25°C, respectively (Royo-Esnal et al., 2015). In the instance that the daily minimum temperature was lower than  $T_b$ , it was set equal to  $T_b$ ; if the daily maximum temperature was higher than the  $T_c$ , the daily temperature was set equal to  $T_c$  (NDAWN Center, 2022). Total GDD were then calculated

by summing the cumulative GDD from planting to the date when the harvest aids were applied (Table 3).

#### *Statistical analysis*

All data was analyzed using linear mixed-effect models constructed using the lmer function of the lme4 package (version 1.1.29) of R 4.1.2 (Bates et al., 2015; R Core Team, 2021). Treatment was considered a fixed effect while year and replication were considered random effects. Biomass moisture at harvest maturity was heteroskedastic and violated the analysis of variance (ANOVA) assumption of equal variances and was  $\log(x)$ -transformed for analysis and back-transformed for presentation. All other data met ANOVA assumptions and did not require transformation prior to analysis. Differences in treatment were determined using a threshold of  $\alpha = 0.05$  with the Anova function of the car package (version 3.0.12) (Fox and Weisberg, 2019). Significance levels for each parameter with respect to harvest aid treatment are presented in Table 4. When significant differences were found ( $P < 0.05$ ), mean separation was conducted using Tukey's Honest Significant Difference (HSD) at  $\alpha = 0.05$ . The emmeans function from the emmeans package (version 1.7.4.1) was used for the mean separation and the cld function from the multcomp package (version 1.4.19) was used to determine the compact letter display associated with the mean separation (Hothorn et al., 2008; Lenth et al., 2022).

## **1.4. RESULTS AND DISCUSSION**

#### *Environmental conditions*

The primary pennycress growing season (*i.e.*, September through November and April through June) over 2018-2019 was cooler and wetter compared with the 30-year

average (Table 2). Average conditions over the 2019-2020 primary growing season were similar to the 30-year average. Despite these differences, conditions between both experimental years had similarities. The autumnal temperature and precipitation rates followed the same pattern across experimental years, however, the growing conditions differed in the spring (Table 2). There were contrasting levels of spring precipitation in 2019 and 2020. While April and May 2019 were consistently wet, the same period in 2020 was exceptionally dry. The opposite was true in June; in 2019 about half of the typical amount of rain fell and in 2020 there was nearly twice as much precipitation as in an average year. Overall, the 2018-2019 primary growing season was 1.3°C cooler and accumulated 140 mm more precipitation than is typical while the 2019-2020 primary growing season was 0.4°C cooler and accumulated only 19 mm more precipitation compared with the 30-year average (Table 2).

#### *Phenological development*

Environmental conditions over the 2018-2019 and 2019-2020 growing seasons had a significant effect on pennycress development milestones. Pennycress that was harvested in 2019 did not reach physiological maturity until 2 July, while the pennycress that was harvested in 2020 followed the expected growth and maturation timeline for Minnesota, reaching physiological maturity on 17 June (Cubins et al., 2022). These differences can likely be attributed to the early spring growing conditions during each experimental year. The monthly temperatures throughout spring 2020 were close to the 30-year normal whereas cooler-than-average temperatures persisted throughout spring 2019 resulting in fewer available GDD (Tables 2 and 5). The pennycress line grown during the 2018-2019 growing season accumulated 1586°C d GDD between planting and physiological maturity

(Table 5). In comparison, it was determined that the wild type ‘MN106’ required 2230-2250°C d GDD to reach physiological maturity in Minnesota when grown under similar conditions (Cubins et al., 2022). This represents about 50% more GDD than was accumulated by the 2018-2019 pennycress in the present experiment. The low temperatures in early spring 2019 may have been the driving force behind these differences, however, this does not take into account the similarly low number of GDD accumulated in 2020 (Table 5). Only 1782°C d GDD were accumulated over the 2019-2020 growing season when pennycress matured at the expected time and temperatures were close the 30-year normal (Tables 2 and 5). Biologically-speaking, pennycress is a long-day plant, meaning that it flowers when days are long after a period of vernalization (Best and McIntyre, 1972). Based on this, ‘IO217’ was likely triggered to flower due to the change in day length alone despite a relative lack of GDD accumulation. The relative differences between the pennycress grown in 2019 and 2020 may have resulted from the shifts in seasonal temperature (Table 2). These results indicate that GDD accumulation may not be as useful a metric to predict pennycress physiological maturity and other variables, such as photoperiod sensitivity, should be taken into account. Future experiments focusing on both flowering time and physiological maturity of ‘IO217’ and other improved pennycress lines with stacked traits will be valuable for further development of pennycress best management practices.

Differences in time and GDD to physiological maturity compared with previous studies also underscored some of the difficulties of targeting management action to specific growth stages. In this experiment, keeping track of phenological development was of critical importance since harvest aid application was targeted to a specific range of growth

stages (Table 3). While this process was slow and drawn out for the majority of the 2019 growing season, pennycress maturation progressed quickly once it reached physiological maturity, which provided a temporal challenge. Rapid pennycress maturation was also observed in 2020 despite the timing of physiological maturity generally matching up with prior research. Pennycress had a slow start to phenological development in 2020, but quickly made up for lost time in June, which was particularly hot and wet (Table 2). In the days prior to physiological maturity in 2020, visual indicators (*i.e.*, seed texture and plant color) suggested that the pennycress stand was still at least a week from reaching physiological maturity (personal observation). However, maturation accelerated from that point as a result of consistent hot temperatures and rapid GDD accumulation (Table 2). Less than a week later the stand was near the end of physiological maturity and harvest aids were applied late relative to the targeted growth stages (Table 3). The speed at which pennycress matured after reaching physiological maturity in conjunction with cost and labor required to apply a harvest aid to pennycress may make harvest aid application an unattractive option for growers considering pennycress for production on their farms.

These difficulties were also compounded by uneven stand maturation, a known issue with pennycress, which made it difficult to estimate pennycress growth stage on a plot-wide level (Sedbrook et al., 2014). It was typical to see plants that were visually mature directly adjacent to plants that were completely green throughout the second half of June 2019 (personal observation). This was likely a product of relatively late pennycress planting in 2018 and the resulting proportion of fall- versus spring-germinated seed. In prior research, early September planting dates led to better establishment than late fall or early spring planting dates (Dose et al., 2017). While germination in both the fall and spring

were not specifically assessed, an earlier planting date in 2018 may have allowed for more consistent fall germination and establishment. In contrast, uneven stand maturation was not as much of an issue with the pennycress grown during the 2019-2020 season, which was planted about two weeks earlier than in the first experimental year. Overall, the ‘IO217’ line in this study was predominantly used for its reduced-shatter mutation, however, it is clear that many of the difficulties associated with growing wild type pennycress still persist and that future breeding targets should continue to focus on consistent germination at planting and uniform stand maturation.

#### *Seed and biomass moisture*

There was a significant reduction in seed and biomass moisture between physiological maturity, when treatments were applied, and harvest maturity, when plants were harvested (data not shown; Fig. 1). This was expected based on the biological parameters that define each stage of development. Physiological maturity is defined as the time when seed has achieved maximum dry weight while harvest maturity corresponds with the time when plant material has dried enough for mechanical harvest, typically when seed moisture is around 120 g kg<sup>-1</sup> (Crookston and Hill, 1978; Martinelli and Galasso, 2011; Mousavi-Avval and Shah, 2020). While the main focus of this study was to examine the differences in biomass and seed moisture between harvest aid treatments at harvest maturity, these parameters were also measured at treatment application (*i.e.*, at or around physiological maturity) as a reference parameter. Plant moisture at physiological maturity is typically too high for mechanical harvest and the seed is too wet for long term storage. The pennycress in this experiment was no exception. Seed moisture at treatment application averaged 191 g kg<sup>-1</sup> across experimental years while biomass moisture

averaged 538 g kg<sup>-1</sup> (data not shown; Fig. 1). Biomass moisture at harvest aid application was similar in both years of the experiment, but it is interesting to note that seed moisture was quite different in each year. In 2019, when harvest aid application more closely aligned with the targeted growth stages, seed moisture averaged 294 g kg<sup>-1</sup> while seed moisture averaged 87 g kg<sup>-1</sup> in 2020 when treatment application occurred late relative to the targeted growth stages (data not shown; Table 3). Based on the differences in growth stage at treatment application each year, 85.5 in 2019 and 86.2 in 2020, these results further demonstrate how rapidly pennycress matures once it reaches physiological maturity (Table 3). It is also important to recognize that pennycress seed in 2020 had nearly reached the recommended moisture content for post-harvest storage, 8 g kg<sup>-1</sup>, prior to treatment application through natural senescence alone (Mousavi-Avval and Shah, 2020). The suggested pennycress seed moisture at harvest is 120 g kg<sup>-1</sup>, so the 2020 pennycress may have been a candidate for direct harvest at the time of treatment application. However, taking the seed moisture at treatment application in 2019 into account, moisture reduction was necessary to facilitate combine harvest. It is interesting to note that, in both years, seed moisture at treatment application was below the estimated range for pennycress seed moisture at physiological maturity, 434-455 g kg<sup>-1</sup>, established in a prior study (Cubins et al., 2022). This may mean that pennycress was past physiological maturity in both years of the study by the time treatment application occurred. In the future, it may be prudent to continuously sample for seed moisture once pennycress begins to mature to better estimate when physiological maturity is imminent. At harvest maturity, seed moisture was similar across treatments (Table 4). The average seed moisture at harvest was 67 g kg<sup>-1</sup>, meaning that pennycress seed was adequately dry for mechanical harvest as well as post-harvest

storage (Table 5; Crookston and Hill, 1978; Mousavi-Avval and Shah, 2020). An important takeaway is that the seed moisture of the treated pennycress was no different than that of the control pennycress, indicating that harvest aid application was not necessary for pennycress seed moisture reduction.

Unlike seed moisture, there were significant differences in biomass moisture between treatments at harvest maturity (Table 4). The swathing treatment produced the driest plants while the Defol treatment and control corresponded with the smallest reduction in biomass moisture (Fig. 1). Plant moisture after swathing decreased to  $82 \text{ g kg}^{-1}$  by the time of harvest while the Defol and control treatments averaged  $193 \text{ g kg}^{-1}$ . There are few directives on optimal biomass moisture content for Brassicaceae harvest. In canola, some green material is acceptable, but it is important to wait until the seed pods are dry enough to allow for seed to separate from the pod (Canola Council of Canada, 2018). In addition, a lower biomass moisture generally makes combine harvest easier with fewer chances of clogging machinery. Given this information, it is possible that pennycress in all treatments in this study were at an appropriate moisture level for combine harvest at harvest maturity despite the statistical differences (Fig. 1). However, if a harvest aid was selected, these results demonstrate that Defol is not an appropriate choice for biomass moisture reduction in pennycress as it did not perform differently from the naturally senescing control. In contrast, Diquat or swathing the pennycress stand may be more effective moisture reduction tools (Fig. 1). Swathing itself comes with challenges. Many farms that are targeted for pennycress production in the Upper Midwest (*i.e.*, corn and soybean operations) have the infrastructure to harvest pennycress through direct combining, but may not have the expertise or equipment readily available for swathing. In comparison with

a chemical desiccant, these challenges may deter a grower from approaching swathing as a harvest method. Overall, it does not appear that a chemical desiccant is a necessary for pennycress production using the current germplasm. As demonstrated, pennycress ripens between mid-June and early July when conditions allow for rapid moisture loss following physiological maturity. However, early maturing pennycress lines are a primary breeding target (Chopra et al., 2020). When these lines are more readily available, it may be prudent to revisit the question of chemical desiccation or swathing prior to harvest as pennycress will hypothetically reach physiological maturity at a time when environmental conditions are cooler and therefore cannot facilitate rapid natural senescence following physiological maturity.

#### *Post-harvest measurements*

There were no differences between treatments in terms of oil content, crude protein, or seed yield (Table 4). This was an expected outcome given that pennycress treatments were deployed at or just after physiological maturity when both oil content and crude protein were fully developed (Table 3; Cubins et al., 2022). Oil content averaged 323 g kg<sup>-1</sup> over both experimental years (Table 5). In comparison, prior research has determined that pennycress oil content typically ranges between 260 and 360 g kg<sup>-1</sup> (Cubins et al., 2019). Maximizing oil content is an important aspect of pennycress production as the primary post-harvest product is oil (Moser, 2012; Mousavi-Avval and Shah, 2020). However, oil yield is a combination of both oil content and seed yield. Pennycress yield in prior research has generally spanned 373-933 kg ha<sup>-1</sup> though a few studies have reported maximum yield values up to 1387 kg ha<sup>-1</sup> (Cubins et al., 2019). The seed yield in this study averaged 2271 kg ha<sup>-1</sup>, much greater than the range typically reported (Table 5; Cubins et

al., 2019). This is largely due to the reduced-shatter *Ta-ind-2* mutation that characterizes ‘IO217’ (Chopra et al., 2020). Prior research has mainly dealt with shatter-prone wild type lines such as ‘MN106’ and ‘Beecher’ meaning that yield loss up to 35% between physiological maturity and harvest maturity was commonplace (Carlson, 2018; Cubins et al., 2022; Dose et al., 2017; Johnson et al., 2017; Ott et al., 2019). While the oil content of seed in this experiment was comparable with prior research, the high seed yield of the ‘IO217’ line greatly increases the oil yield potential after pennycress harvest.

Crude protein values were low relative to the values presented in prior pennycress research. Crude protein in the present study averaged 188 g kg<sup>-1</sup> across experimental years while pennycress in prior studies has reached levels between 230 and 270 g kg<sup>-1</sup> (Table 5; Dose et al., 2017; Cubins et al., 2022). It is unclear why the crude protein content in this study was so low relative to prior research as similar rates of N were applied across experiments. There are trade-offs between oil content and crude protein, as oil is the primary form of carbohydrate storage in mature oilseeds (Da Silva et al., 1997; Focks and Benning, 1998; Vigeolasetal et al., 2004). However, the oil content of this pennycress seed does not seem high enough to necessitate a lower crude protein content. While crude protein is not a primary concern in pennycress production right now, this may become more important in the future as there is an interest in pennycress meal for use as a nutritional supplement for livestock (Hojilla-Evangelista et al., 2015, 2013).

## **1.5. CONCLUSIONS**

Based on these results, harvest aids may not be a necessary tool in pennycress production at this time. Pennycress seed and biomass moisture was reduced at nearly the

same rate for treated and untreated pennycress, indicating that harvest aids are not currently necessary. Natural senescence is not only a physiologically efficient strategy for pennycress plant maturation, it also does not add to the material and labor costs of pennycress production like the addition of a harvest aid would. At present, the time between pennycress physiological and harvest maturity occurs when GDD are generally plentiful, meaning that the time between these milestone development stages is very short. However, this may change in the future. Early-maturing pennycress is a primary breeding target and when these pennycress lines are developed, they will reach physiological maturity earlier in the growing season when temperatures are cooler. This may necessitate another look at harvest aids once the window between physiological and harvest maturities lengthens.

While this experiment was not a germplasm study, the improvements and drawbacks of the 'IO217' line were evident. Many of the challenges faced in this experiment, such as uneven stand germination and late maturation, stemmed from known issues with unimproved pennycress lines. It is clear that the development of further improved pennycress lines with stacked traits will be essential to successful production in the Upper Midwest. However, seed shatter has been a principal concern in pennycress research and production and the reduced-shatter mutation that is present in the 'IO217' line resulted in a significant increase in harvestable seed. This mutation alone was able to increase potential pennycress oil production by two to seven times the amount predicted from the pennycress lines used in prior research regardless of the stand maturation issues. This is important as oil is the primary product of pennycress production. Future

improvements and trait stacking will continue to improve the viability of pennycress as an agricultural crop on the Upper Midwest landscape.

## **1.6. TABLES AND FIGURES**

Table 1-1. Baseline soil samples of the trial sites for the 2018-2019 and 2019-2020 growing seasons.

| Growing season | pH             | OM                 | CEC                 | Inorganic N        | P                   | K   | Ca   | Mg  |
|----------------|----------------|--------------------|---------------------|--------------------|---------------------|-----|------|-----|
|                | H <sup>+</sup> | g kg <sup>-1</sup> | meq g <sup>-1</sup> | g kg <sup>-1</sup> | mg kg <sup>-1</sup> |     |      |     |
| 2018-2019      | 5.9            | 4.7                | 0.227               | 0.218              | 31                  | 158 | 1900 | 435 |
| 2019-2020      | 6.0            | 4.1                | 0.225               | 0.171              | 15                  | 90  | 1954 | 460 |

Table 1-2. Mean monthly air temperature and cumulative precipitation over the 2018-2019 and 2019-2020 growing season and the 30-year normal (1991-2020) for Rosemount, MN experimental site.

| Month | 2018-2019   |         |               |        | 2019-2020   |        |               |        |
|-------|-------------|---------|---------------|--------|-------------|--------|---------------|--------|
|       | Temperature |         | Precipitation |        | Temperature |        | Precipitation |        |
|       | Mean        | Normal† | Total         | Normal | Mean        | Normal | Total         | Normal |
|       | °C          |         | mm            |        | °C          |        | mm            |        |
| Sept  | 17.4        | 16.2    | 157           | 87     | 17.6        | 16.2   | 146           | 87     |
| Oct   | 6.2         | 8.7     | 91            | 73     | 6.8         | 8.7    | 109           | 73     |
| Nov   | -3.3        | 0.3     | 38            | 43     | -2.1        | 0.3    | 27            | 43     |
| Dec   | -5.0        | -7.1    | 47            | 31     | -6.6        | -7.1   | 35            | 31     |
| Jan   | -11.1       | -10.7   | 12            | 24     | -7.7        | -10.7  | 58            | 24     |
| Feb   | -13.2       | -8.3    | 73            | 23     | -8.5        | -8.3   | 15            | 23     |
| Mar   | -4.3        | -1.0    | 58            | 46     | 1.1         | -1.0   | 35            | 46     |
| Apr   | 6.5         | 7.1     | 121           | 79     | 6.1         | 7.1    | 8             | 79     |
| May   | 11.6        | 14.0    | 173           | 110    | 13.6        | 14.0   | 57            | 110    |
| June  | 19.9        | 19.6    | 76            | 124    | 21.1        | 19.6   | 228           | 124    |
| July  | 22.7        | 21.7    | 180           | 115    | 23.1        | 21.7   | 58            | 115    |

† The 30-year air temperature and cumulative precipitation averages from 1991-2020 were available for the Rosemount Research and Outreach Center.

Table 1-3. Harvest aid treatments active ingredients and rates and the intended pennycress growth stage at application versus actual growth stage at application during the 2019 and 2020 growing seasons.

| Treatment | Active ingredient | Rate<br>L ha <sup>-1</sup> | Growth stage at application† |      |      |
|-----------|-------------------|----------------------------|------------------------------|------|------|
|           |                   |                            | Intended                     | 2019 | 2020 |
| Defol 1   | Sodium chlorate   | 4.7                        | 85-86                        | 86.0 | 87.3 |
| Defol 2   | Sodium chlorate   | 9.4                        | 85-86                        | 85.2 | 85.5 |
| Diquat 1  | Diquat dibromide  | 2.3                        | 85-86                        | 85.3 | 86.5 |
| Diquat 2  | Diquat dibromide  | 4.7                        | 85-86                        | 86.5 | 85.6 |
| Swath     | -                 | -                          | 85-86                        | 84.6 | 86.0 |

† Growth staging based on the extended BBCH scale for camelina (Martinelli and Galasso, 2011).

Table 1-4. Mixed effects model analysis of variance for in-season and post-harvest parameters by harvest aid treatment.

| Fixed effect | Seed moisture | Biomass moisture | Seed yield | Oil content | Crude protein |
|--------------|---------------|------------------|------------|-------------|---------------|
| Harvest aid  | ns‡           | ***†             | ns         | ns          | ns            |

† \*, \*\*, and \*\*\* refers to parameters with p-values of 0.05, 0.01, and 0.001, respectively, for a given fixed effect.

‡ ns refers to parameters that were not significant for the given fixed effect.

Table 1-5. Pennycress cumulative growing degree days (GDD) at physiological maturity and mean values for pennycress harvest parameters at harvest maturity over the 2018-2019 and 2019-2020 growing seasons and the overall average for both experimental years.

| Growing season | Cumulative GDD | Seed yield†         | Seed moisture      | Oil content‡ | Crude protein‡ |
|----------------|----------------|---------------------|--------------------|--------------|----------------|
|                | °C d           | kg ha <sup>-1</sup> | g kg <sup>-1</sup> |              |                |
| 2018-2019      | 1586           | 1962                | 57                 | 309          | 153            |
| 2019-2020      | 1782           | 2580                | 78                 | 337          | 224            |
| Mean           | 1684           | 2271                | 67                 | 323          | 188            |

† Presented at 80 g kg<sup>-1</sup> moisture content.

‡ Presented on a dry matter basis.

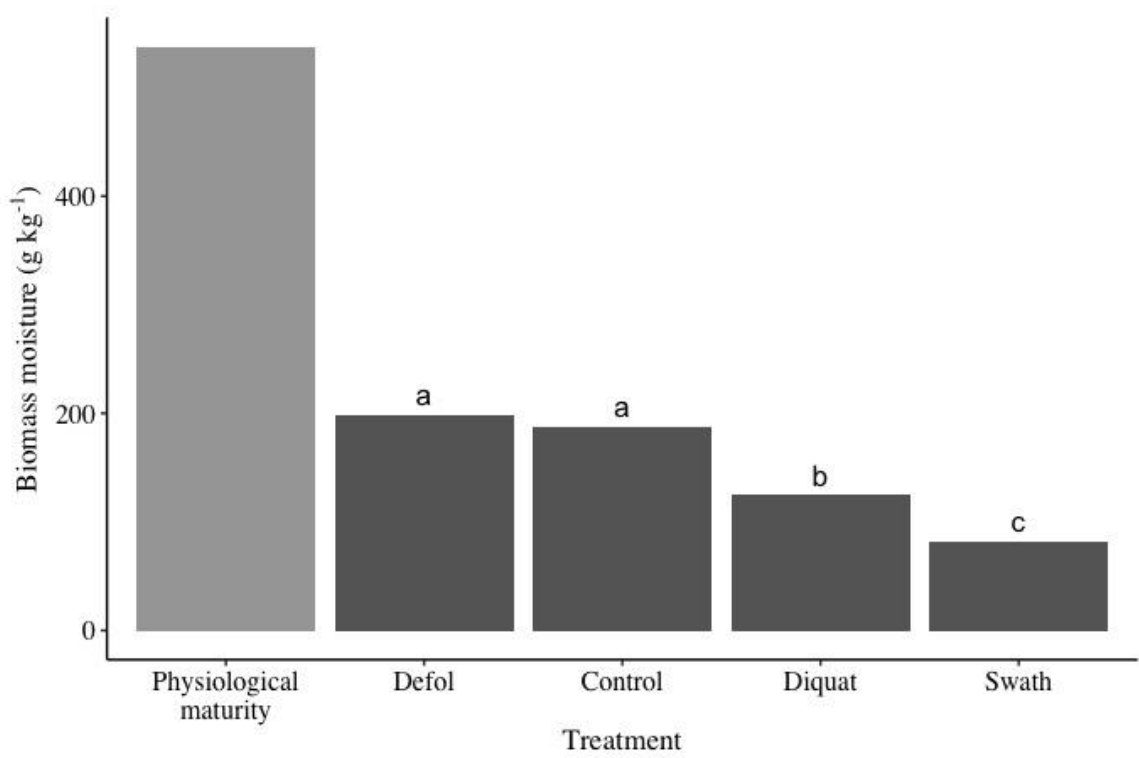


Figure 1-1. Biomass moisture of non-shatter pennycress at harvest maturity over the 2018-2019 and 2019-2020 growing seasons. Treatments that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ).

## **2. AGRONOMIC AND ECONOMIC TRADE-OFFS OF INTEGRATING CAMELINA INTO THE CORN-SOYBEAN ROTATION**

### **2.1 SUMMARY**

Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr.) account for the much of the arable land in the Upper Midwest during the summer, but land is left fallow in the late fall after harvest through early spring leaving valuable growing degree days unused. Temporal intensification is a concept that can integrate crops such as winter camelina (*Camelina sativa* L.) onto the landscape during these fallow periods. Winter camelina is a winter annual oilseed that can survive the harsh winter conditions in the Upper Midwest while providing an economic benefit to farmers the following spring. However, there are significant agronomic and economic trade-offs associated with integrating camelina into the corn-soybean rotation. The objectives of this study were to assess the yield potential and seed quality of a corn-camelina-soybean rotation utilizing a range of corn hybrid maturities; evaluate camelina establishment in environments with and without corn stover; and calculate the economic trade-offs of the typical corn-soybean rotation versus including camelina. This study was conducted over the 2019 and 2020 growing seasons at two locations in Minnesota, USA. Corn and soybean seed yields were maximized in treatments that were unfavorable to camelina and vice versa. Corn stover presence had a negative effect on camelina establishment and yield, but was favorable to soybean production. Based on both the agronomic and economic analyses for the aggregated cropping system, treatments that began with the 90 and 95 RM corn hybrids performed equally well, regardless of stover presence, indicating that there are multiple options to move forward with a corn-camelina-soybean cropping rotation.

## 2.2. INTRODUCTION

Agricultural land across the United States is dominated by summer annual crop species such as corn and soybean. These commodity crops are grown in large swaths across the Upper Midwest and, in 2020, accounted for 6.2 million hectares of production land in Minnesota alone (USDA National Agricultural Statistics Service, 2021a, 2021b). While corn and soybean account for a large portion of annual biomass and seed production in the Upper Midwest, these summer crops leave land fallow during the late fall and early spring when environmental conditions are still conducive for crop growth (Heggenstaller et al., 2008). This unused production land can be leveraged through temporal intensification, a practice where a secondary crop is grown during the fallow season (*i.e.*, September through April) and harvested for a marketable product (Heaton et al., 2013; Sindelar et al., 2017). However, there are limitations to the crops that can be produced during this period due to climatic, temporal, and economic challenges. Growing a crop during the fallow season in the Upper Midwest limits growers to winter crops that are able to survive extremely low temperatures. In this region, the USDA plant hardiness zones range from 5b to 3a, indicating that the temperature can drop as low as  $-40^{\circ}\text{C}$  in the winter, depending on location (USDA Agricultural Research Service, 2012). In addition, low temperatures during the fallow season necessitate that a secondary crop established during this time must have a low growing temperature threshold. Considering these constraints alone, there are a limited number of species that can be planted during the winter season. One such crop is cereal rye (*Secale cereale* L.), which is the most common winter annual species grown in the United States (Crop Technology Information Center, 2020; Wallander et al., 2021). While cereal rye fits within the climatic constraints of the Upper Midwest, it is typically

terminated in the spring while in its vegetative stage and does not yield a marketable product (Mirsky et al., 2009; Wells et al., 2016). Winter cover alone can provide important environmental benefits, such as reducing soil erosion and nutrient sequestration, but the current practices surrounding cereal rye adoption demonstrate two significant challenges that have limited the adoption of winter crops: balancing the harvest and planting of back-to-back crops and the lack of short-term economic return associated with winter crops (Crop Technology Information Center, 2020; Roesch-McNally et al., 2017). In fact, these temporal and economic constraints have led many farmers to avoid planting winter crops entirely despite a desire to implement conservation practices (Crop Technology Information Center, 2020). This highlights the need for winter annual crops that can survive the cold temperatures of the Upper Midwest, have a relatively short lifecycle, and can provide near-term economic benefits.

One alternative crop that fits within these limitations is winter camelina. Camelina is a small-seeded Brassicaceae that originated in southeast Europe and southwest Asia, but has been naturalized to many environments around the globe, including the Upper Midwest (Berti et al., 2016; Ehrensing and Guy, 2008). Prior research has demonstrated that winter camelina can survive Minnesota winters and accumulate growing degree days at temperatures as low as  $-0.7^{\circ}\text{C}$ , making it a good climatic fit for the Upper Midwest (Allen et al., 2014; Gesch and Cermak, 2011). Camelina is also a good economic fit for the region due to its relatively high seed oil content, which can be used as both an edible oil and an industrial feedstock (Berti et al., 2016; Moser, 2012). In addition, there is interest in using camelina meal, a by-product of the oil pressing process, as a source of plant protein due to its high protein content ( $25\text{-}30\text{ g kg}^{-1}$ ) and its nutritional similarity to both canola (*Brassica*

*napus* L.) and soybean meal (Kleba and Ismail, 2018). The markets for camelina end-products are currently in development, but the numerous pathways indicate that there is a lot of potential for economic expansion surrounding camelina and its products. While camelina is a good fit in terms of the environmental and economic conditions required of a winter crop grown in the Upper Midwest, there are temporal challenges associated with adding camelina to the corn-soybean rotation.

Despite its relatively short lifecycle, camelina is typically harvested in late June to early July meaning that it overlaps significantly with the summer annual growing season (Walia et al., 2018). Prior research has indicated that this can be remedied by double- or relay-cropping camelina with soybean, but there are yield trade-offs associated with this practice (Gesch et al., 2014; Johnson et al., 2017; Ott et al., 2019). Soybean yield is often reduced by the addition of camelina, but these reductions have the potential to be offset by the harvested camelina, both agronomically and economically. However, it is important to remember that soybean represents just one half of the current cropping rotation and the temporal concerns of harvesting corn and planting camelina in a relatively short period of time also need to be considered. Full season corn hybrids are harvested between late September and late November in the Upper Midwest, leaving little time for planting, germination, and establishment of a winter species (USDA National Agricultural Statistics Service, 2010). This tight window has been a principal concern to growers who are interested in adopting a secondary crop (Roesch-McNally et al., 2017). One way to remedy this issue is to create a larger time period for autumnal field activities through the use of short-season corn hybrids, which can be harvested earlier than their full season counterparts. Short-season corn hybrids are known to yield less than their full season

counterparts, but, similar to soybean, the addition of camelina may be able to compensate for any corn yield depression that occurs (Assefa et al., 2016). The corn stover itself presents another issue. The Upper Midwest predominantly produces grain corn, which leaves a significant amount of stover on the ground when harvested (USDA National Agricultural Statistics Service, 2021b; Wilhelm et al., 2004). At the same time, camelina is a small-seeded crop and good seed-soil contact is critical for seed germination, so it can be difficult for camelina to establish in a high residue environment (Grady and Nleya, 2010; Hunter and Roth, 2010; McVay and Lamb, 2008). This is particularly important if camelina is to be used as winter cash crop rather than a cover crop because high yield, and, by default, good germination is necessary to offset the costs of production and ensure cropping system profitability. One solution to this may be removing corn stover prior to camelina planting. Thus, the objectives of this study were to (1) assess the yield potential and seed quality of a corn-camelina-soybean rotation utilizing a range of corn hybrid maturities, (2) evaluate camelina establishment in environments with and without corn stover, and (3) calculate the economic trade-offs of including camelina in the rotation compared with the typical corn-soybean rotation.

### **2.3. MATERIALS AND METHODS**

#### *Cultural practices*

This experiment was conducted over the 2019 and 2020 growing seasons at the USDA-ARS Swan Lake Research Farm near Morris, MN (45°41'12" N 95°48'12" W) and at the University of Minnesota Rosemount Research and Outreach Center in Rosemount, MN (44°42'35" N 93°04'18" W). The soil at the Morris site was classified as a Barnes

loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) and the soil at the Rosemount site was classified as a Waukegan silt loam (fine-silty over sand-skeletal, mixed, superactive, mesic Typic Hapludoll).

Monthly precipitation and mean air temperature were recorded by weather stations at each site (Table 2-1). The 30-year air temperature and precipitation averages from 1991-2020 were obtained from sites in close proximity to the research sites (National Centers for Environmental Information, 2021). Thirty-year averages for the Morris research site were obtained from the West Central Research and Outreach Center in Morris, MN, which is approximately 18 km from the study location. Thirty-year averages were directly available for the Rosemount Research and Outreach Center.

#### *Experimental design*

The experimental design was a split-plot randomized complete block design with four replicates. The main plot treatment was corn hybrid relative maturity. The split plot treatment was the presence or absence of corn stover following corn harvest. The field management practices for this experiment are summarized in Table 2-2. Plot size at the Morris site was 3.0 m x 9.1 m and 3.0 m x 12.2 m at the Rosemount site. Both sites were prepared and planted with corn in May 2019. The crop preceding corn at the Morris site was soybean while the crop preceding corn at the Rosemount site was soybean followed by a rye cover crop. The field at the Morris site was prepared using a chisel plow and the seedbed was fertilized at a rate of 168-67-67-11 kg ha<sup>-1</sup> N-P-K-S prior to corn planting. The trial area at the Rosemount site was prepared using a chisel plow and then was disked to prepare the seedbed. The seedbed was then fertilized at a rate of 157-117-135-20 kg ha<sup>-1</sup> of N-P-K-S and incorporated with cultivation. Corn was planted on 6 May 2019 at the

Morris site at a rate of 84,757 seeds ha<sup>-1</sup> using a seed drill with 76 cm row spacing. Corn was planted on 7 May 2019 at the Rosemount site using a seed drill with 76 cm row spacing at a rate of 87,969 seeds ha<sup>-1</sup>. Three relative maturities of corn were planted: an 82-day hybrid (Dekalb ‘DKC 32-12’); a 90-day hybrid (Dekalb ‘DKC 40-77’); and a 95-day hybrid (Dekalb ‘DKC 45-65’). These hybrids were chosen because they span the range from a short-season hybrid that would mature early enough to give ample time for winter camelina to establish before the first frost (*i.e.*, the 82-day hybrid) to a typical full-season corn hybrid that could reach full maturity at both experimental sites (*i.e.*, the 95-day hybrid) (Abendroth et al., 2021; Gesch and Cermak, 2011). Within each replicate, there were four plots of 82-day corn, two plots of 90-day corn, and two plots of 95-day corn. At Morris, corn was treated with glyphosate [N-(phosphonomethyl) glycine<sup>3</sup>] (1.1 kg a.i. ha<sup>-1</sup>) on 6 and 18 June and with bromoxynil [3,5-dibromo-4-hydroxybenzotrile] (0.28 kg a.i. ha<sup>-1</sup>) on 18 and 27 July for weeds. At Rosemount, corn was treated with glyphosate [N-(phosphonomethyl) glycine<sup>3</sup>] (1.1 kg a.i. ha<sup>-1</sup>) on 23 May and 12 June for weeds. Corn at the Rosemount site was also hand weeded in July 2019. Each corn relative maturity was harvested once the kernels reached 250 g kg<sup>-1</sup> moisture. At Morris, the 82-, 90-, and 95-day hybrids were combine harvested on 24 September, 8 October, and 18 October 2019, respectively. At Rosemount, a 3-m row of each hybrid was hand harvest prior to bulk harvest with a combine. The 82-, 90-, and 95-day hybrids were hand harvested on 26 September, 8 October, and 16 October 2019, respectively, and then bulk harvested within two days. Corn from each plot was assessed for yield, test weight, and seed moisture. Prior to analysis and presentation, corn seed yield was adjusted to a moisture content of 155 g kg<sup>-1</sup>.

Following bulk harvest, stover was removed from half of the plots, so, within each replicate, there were two 82-day corn plots with and without stover and one plot with and without corn stover for both the 90- and 95-day corn hybrids. Stover was removed using a Lely weeder (Lely Turf Products, Pella, IA) at the Morris site and hand raked at the Rosemount site. One set of the 82-day hybrid plots (one with and one without stover) were used as the experimental controls. The rest of the plots were no-till planted with camelina (cultivar Joelle) following corn harvest using an InterSeeder (InterSeeder Technologies, Woodward, PA) after stover removal had occurred in the ‘no stover’ plots. Camelina was planted at the Morris site on 24 September, 8 October, and 18 October 2019 after the harvest of the 82-, 90-, and 95-day corn hybrids, respectively. Camelina was planted at a rate of 11.5 kg ha<sup>-1</sup> with 19 cm row spacing and there was a skip row (*i.e.*, no camelina planted) every 76 cm. Camelina was planted at the Rosemount site on 26 September, 9 October, and 18 October 2019 following the bulk harvest of the 82-, 90-, and 95-day corn hybrids, respectively. Camelina was planted at a rate of 11.2 kg ha<sup>-1</sup> with 19 cm row spacing and a skip row every 76 cm to account for the corn stubble. Fertilizer was broadcast by hand at both sites in April 2020 after the soil had thawed. The rate at the Morris site was 56-34-34 kg ha<sup>-1</sup> while the rate at the Rosemount site was 79-34-34 kg ha<sup>-1</sup> of N-P-K. The center camelina rows were combine harvested at the Morris site on 6 July. Camelina was hand harvested on 6 July at the Rosemount location as the camelina and soybean were similar heights and the camelina could not be mechanically harvested. The camelina was harvested from a 0.25 m<sup>2</sup> area at the Rosemount site for yield. Prior to analysis and presentation, camelina seed yield was adjusted to a moisture of 80 g kg<sup>-1</sup>.

Soybean was relay planted into camelina with a no-till drill prior to camelina bolting in spring 2020. The soybean planted at the Morris location was a 1.1 maturity group bean (NK ‘S11-E3’) while the soybean planted at the Rosemount location was a 2.0 maturity group bean (Asgrow ‘AG20X’), which reflected the typical maturity for a relay-cropped bean for both sites. All plots were planted with soybean at the Morris site on 7 May 2020. Rosemount had two soybean planting dates due to delayed camelina maturation in the 95-day corn hybrid plots. The plots where the 82- and 90-day corn hybrids had grown were planted with soybean on 8 May and soybean was no-till planted into the 95-day corn plots on 20 May 2020. Soybean was planted at a rate of 432,434 and 380,542 seeds ha<sup>-1</sup> with 76 cm row spacing at Morris and Rosemount, respectively. Soybean plots at Morris were sprayed with glufosinate [2-amino-4-[hydroxy(methyl)phosphoryl]butanoic acid] (0.47 kg a.i. ha<sup>-1</sup>) for weed control on 23 July. Plots at Rosemount were treated with glyphosate [N-(phosphonomethyl) glycine<sup>3</sup>] (1.1 kg a.i. ha<sup>-1</sup>) following camelina harvest on 10 and 31 July to reduce weed pressure and terminate any remaining camelina plants; the soybean was also hand weeded in mid-July. Soybean was combine harvested on 6 October in Morris and on 30 October in Rosemount. Seed was assessed for yield, test weight, and seed moisture at harvest. Prior to analysis and presentation, soybean seed yield was adjusted to a moisture content of 130 g kg<sup>-1</sup>.

#### *In-season measurements*

Camelina ground cover was assessed two weeks after the final camelina planting date in November 2019 and again in April 2020 following spring thaw. Ground cover was measured using the Canopeo app as a percent of the total green cover in the captured area (Oklahoma State University, Stillwater, OK). The measured area was 2000 cm<sup>2</sup> and 7600

cm<sup>2</sup> at the Morris and Rosemount sites, respectively. At both locations, measurements were taken from the center row of the camelina plot. In some plots at the Rosemount site, center rows did not have any vegetative cover due to planter error. In these instances, an adjacent row was chosen for ground cover measurements and was used for both the autumn and spring measurements.

#### *Plant analysis*

Following harvest, camelina and soybean seed was assessed for seed oil content using pulsed nuclear magnetic resonance (NMR) with a Minispec mq-10 (Bruker, The Woodlands, TX). Camelina and soybean seed was dried at 130°C for 3 h, cooled in a desiccator for 30 min, and a 5-6 g subsample was used for analysis. Prior to analysis, the NMR instrument was calibrated using pure oil from the seed of each of the crops. Values for oil content are reported as g kg<sup>-1</sup> (dry wt oil/dry wt seed). Camelina and soybean seed was also analyzed for percent nitrogen and carbon content. Samples were dried at 65°C, ground, and passed through a 420 µm mesh sieve. Approximately 200 mg of ground material was measured out for analysis with a Leco CN-2000 combustion analyzer (Leco Corporation, St. Joseph, MI). Seed crude protein content was then estimated by multiplying total N by 6.25 (Gesch et al., 2014).

#### *Economic analysis*

The gross approximate processed value (APV) was calculated for corn, camelina, and soybean individually and the net APV was calculated for the cropping system as a whole. The APV for corn was calculated by multiplying the yield on a dry weight basis by the corn price while the APVs for camelina and soybean were calculated using the estimated oil and meal production to account for both oil and meal value of the crops. Oil

production at treatment  $i$  ( $O_i$ ) for camelina and soybean at each of the treatments was calculated as:

$$O_i = Y_i \times \left( \frac{C_i}{100} \right); \quad (1)$$

where  $Y_i$  is the yield at treatment  $i$  and  $C_i$  is the seed oil content at treatment  $i$ . Meal production at treatment  $i$  ( $M_i$ ) for soybean and camelina was calculated as:

$$M_i = Y_i \times \left( \frac{100 - C_i}{100} \right); \quad (2)$$

The approximate processed value was then calculated using Eq. 4 (Gesch et al., 2014).

$$APV_i = (O_i \times P_o) + (M_i \times P_m) \quad (3)$$

where  $APV_i$  is the approximate processed value of treatment  $i$ ,  $O_i$  is the oil yield for treatment  $i$ ,  $P_o$  is the oil value,  $M_i$  is the calculated meal yield at treatment  $i$ , and  $P_m$  is the meal price. The net APV was calculated as the sum of the corn, camelina, and soybean APVs minus the summed costs of production for each crop within a treatment.

The value of corn and soybean was determined based on the seed, meal, and oil prices associated with each crop averaged between 2018 and 2021 (USDA Foreign Agricultural Service, 2022, 2020, 2019, 2018; USDA National Agricultural Statistics Service, 2022). The average value of corn seed over this period was \$0.16 kg<sup>-1</sup> while the average value of soybean oil and meal were \$0.84 kg<sup>-1</sup> and \$0.37 kg<sup>-1</sup>, respectively. The costs of corn and soybean production were estimated for 2018 through 2021 using the average costs for the Northern Crescent and Heartland regions of the United States, which encompassed the study locations (USDA Economic Research Service, 2021a). The average cost of corn production between 2018 and 2021 was \$825.33 ha<sup>-1</sup> while the cost of soybean production was estimated at \$457.56 ha<sup>-1</sup>. These costs were defined as the operating costs,

which included the cost of seed, fertilizer, feed, chemicals, and interest on operating capital (USDA Economic Research Service, 2021b). It is important to note that these costs did not include the cost of hired labor.

As camelina does not have a well-established market in the United States, the price of canola oil and meal were used as a proxy for the camelina oil and meal values, respectively. The estimated canola oil and meal prices averaged from 2018 through 2021 were \$1.02 kg<sup>-1</sup> and \$0.84 kg<sup>-1</sup>, respectively (Canola Council of Canada, 2021; USDA Foreign Agricultural Service, 2022, 2020, 2019, 2018). Meal prices were converted from Canadian dollars to U.S. dollars using the exchange rate from the month and year that corresponded with the pricing data. Camelina operating costs were estimated using a 2016 production estimate, which was converted from Canadian dollars to U.S. dollars using the exchange rate from the month and year in the analysis and updated to reflect the prices in 2018-2021 using the Consumer Price Index (Li and Mupondwa, 2016). The average input cost for camelina was \$341.21 ha<sup>-1</sup>. The input costs similarly included the cost of seed, fertilizer, machinery, and interest on operating capital, among other costs (Li and Mupondwa, 2016).

### *Statistical analysis*

The experimental data were analyzed using a linear mixed-effects model in R (R Core Team, 2021). Models were constructed using the lmer function of the *lme4* package (version 1.1.29) (Bates et al., 2015). All data were analyzed with replication as a random effect. The fixed effects varied depending on when data for each parameter was collected. All data collected prior to and at corn harvest were analyzed with corn relative maturity as the only fixed effect (Tables 2-3 and 2-5). Following corn harvest and stover removal, the

fixed effects for the camelina data were corn relative maturity, stover, and the interaction between the two parameters (Table 2-3). The corn and camelina data were analyzed with the locations combined as there were no statistical differences between the two experimental sites and location was treated as a random effect with rep nested within each location (Tables 2-3, 2-4, and 2-5). The two locations were split for soybean yield analysis as different maturity groups were used at each site (Table 2-2). The fixed effects for soybean were corn relative maturity, stover, and the interaction between the two parameters while replication was treated as a random effect (Tables 2-3, 2-4, and 2-5). Plots without camelina acted as controls representing the traditional corn-soybean rotation under a grain and silage corn scenario with stover remaining and removed, respectively. Soybean seed quality data did not differ across locations and were combined for analysis with both location and replication treated as random effects (Table 2-4). The aggregate yield data was also analyzed separately for each location with corn relative maturity, stover presence, and the interaction treated as fixed effects (Table 2-3). The economic data followed the same analysis for individual crop parameters and the aggregate yield data where the corn and camelina data were combined across locations while the soybean and aggregate data were split between locations (Table 2-5).

Following model fitting, each model was assessed for analysis of variance (ANOVA) assumptions. Data that did not meet assumptions were  $\log(x)$ -transformed for analysis and back-transformed for presentation. Data that met assumptions were analyzed using an ANOVA ( $\alpha = 0.05$ ) procedure with Anova function of the *car* package (version 3.0.12) (Fox and Weisberg, 2019). When significant differences were found ( $P < 0.05$ ), a mean separation was conducted using Tukey's Honest Significant Difference (HSD) at  $\alpha$ .

= 0.05. The *emmeans* (estimated marginal means) function from the *emmeans* package (version 1.7.4.1) was used to conduct the mean separation and the *cld* function from the *multcomp* package (version 1.4.19) was used to determine the compact letter display associated with the mean separation (Hothorn et al., 2008; Lenth et al., 2022).

## 2.4. RESULTS AND DISCUSSION

### *Environmental conditions*

Air temperature at both experimental sites over the 2019 and 2020 growing seasons was similar to an average year when compared with the 30-year normal during the periods of corn, camelina, and soybean growth (Table 2-1). Both the Morris and Rosemount sites experienced a warmer-than-typical winter (*i.e.*, December through March) over the period of camelina growth where the average temperature was 1.5 and 1.4°C warmer, respectively, than the 30-year normal temperature across the same months (Table 2-1). Despite the warmer temperatures, camelina growth and development was likely minimally affected as the calculated camelina base temperature is -0.7°C (Allen et al., 2014). Overall, the average temperature at the Morris location over the corn, soybean, and primary camelina growing seasons (*i.e.*, September through November and April through July) was 16.0, 16.5, and 12.1°C and deviated from normal by 0.1, 0.3, and 0.4°C, respectively (Table 2-1). At the Rosemount location, the average temperature over the corn, soybean, and primary camelina growing seasons was 15.9, 16.5, and 12.3°C and deviated from normal by 0.9, 0.3, and 0.2°C, respectively.

Precipitation during the corn growing season (*i.e.*, May through October) was higher than usual while precipitation during the soybean growing season was lower than

usual (Table 2-1). Throughout the 2019 growing season, 689 and 778 mm of precipitation fell at the Morris and Rosemount sites, compared with the 30-year normal of 516 and 621 mm, respectively. The elevated levels of precipitation were noticeable at both locations in May, August, and September, and additionally during the month of July in Rosemount (Table 2-1). In contrast, there was a precipitation deficit throughout the 2020 growing season compared with the 30-year normal (Table 2-1). Overall, the Morris site received 141 mm less precipitation than in a normal year, while the Rosemount site received 73 mm less precipitation. This was especially evident in May and September at both locations, and additionally during the month of July at the Rosemount site, during which 50-60 mm less rain than is typical fell. While precipitation during periods of camelina growth was similar to the 30-year normal, precipitation deviated from normal at multiple points throughout the primary camelina growing season (Table 2-1). Some of this deviation overlapped with that observed during the corn and soybean growing seasons (*i.e.*, September 2019 and May 2020 at both locations). However, precipitation was also notably absent during April 2020 at the Rosemount location when only 8 mm of precipitation was recorded throughout the month, compared with 79 mm in a typical year.

#### *Corn yield*

Corn relative maturity had a significant effect on corn seed yield (Table 2-3). The 95-day corn produced the highest yield followed by the 90-day corn with the 82-day corn having the lowest seed yield (Fig. 2-1). Yield gradation was an expected finding given that short season corn hybrids are known to yield less than full maturity corn hybrids grown in the same locations (Assefa et al., 2016). Compared with county-wide yield data, the average yield of the 90- and 95-day corn hybrids exceeded the county averages for both

locations while the 82-day corn fell below the county averages (Fig. 2-1; USDA National Agricultural Statistics Service, 2021b). At Morris, the 82-day corn yield was lower-than-expected at the Morris site due to bird predation (red-winged blackbirds; *Agelaius phoeniceus* L.) in mid-to-late August. This created a much larger yield gap between the hybrids at the Morris site compared with the hybrids grown at the Rosemount site. The 82-day corn at the Morris site yielded 56% less than the 90-day corn and 62% less than the 95-day corn while the 82-day corn at the Rosemount site yielded only 14% and 18% less than the 90- and 95-day corn, respectively (data not shown). While the reported corn yield reduction was an unfortunate occurrence, it represents a real-world scenario of unprecedented yield loss, and, as a result, these data may not adequately portray the viability of the short season corn in this cropping rotation.

#### *Camelina seed yield*

While corn yield increased with corn relative maturity, the inverse was true for camelina yield (Figs. 2-1 and 2-2). In this experiment, corn relative maturity acted as a proxy for camelina planting date where a longer season corn hybrid corresponded with a later camelina planting date (Table 2-2). Camelina planted following the 82-, 90-, and 95-day corn hybrids yielded, on average, 1251, 966, and 625 kg ha<sup>-1</sup>, respectively, and were all significantly different from one another (Fig. 2-2). Although winter camelina yields up to 2300 kg ha<sup>-1</sup> have been reported in the Upper Midwest, it is more common for camelina to yield between 421 and 1324 kg ha<sup>-1</sup>, which corresponds with the yields observed in this study (Fig. 2-2; Gesch and Cermak, 2011; Berti et al., 2016; Walia et al., 2018; Wittenberg et al., 2020). Winter camelina yields were the highest when planted between early

September and mid-October, which is also in line with these data (Fig. 2-2; Gesch and Cermak, 2011; Wittenberg et al., 2020).

Following the mid-October planting date, the cooler-than-average temperatures did not provide an optimal environment for camelina germination and establishment (Tables 2-1 and 2-2). Research on spring camelina concluded that, when seed was exposed to a constant temperature of 4°C, it took nine days for maximum germination to occur (Russo et al., 2010). In comparison, when spring camelina seed was exposed to a temperature of 0°C, it took 68 days for seedlings to emerge, indicating that, while growth and development can occur near the base temperature, it is delayed (Allen et al., 2014). At both experimental sites, the temperature following the first planting date was consistently above 4°C for more than three weeks after planting, which likely promoted camelina seed germination (data not shown). The temperature was above 4°C for twelve days following the second planting date and only seven days following the third planting date. This may have delayed the germination of camelina from the third planting date and, to a lesser degree, the second planting date, until the following spring. This was corroborated by the autumn ground cover measurements. The third planting date had almost no cover in autumn 2019, indicating that effectively all germination and establishment occurred in spring 2020 (Table 2-6). Overall, the percent ground cover in the autumn was an early reflection of camelina seed yield where the first planting date had the most vegetative cover and the ground cover and subsequent yield decreased over each of the later planting dates (Fig. 2-2; Table 2-6). In fact, it has been demonstrated that seedlings that emerge in the autumn produce more seeds than those that emerge in the spring (Gesch et al., 2016). When measured again in spring 2020, all treatments indicated that early-season camelina growth had occurred

following spring thaw (Table 2-6). However, the camelina planted following the 82-day corn benefitted from the head start in the autumn and had a greater amount of vegetative cover compared with the other two treatments.

In addition to corn relative maturity, camelina yield was also affected by corn stover presence. Plots where corn stover was removed prior to camelina planting yielded an average of 1078 kg ha<sup>-1</sup> while plots with corn stover present yielded an average of 830 kg ha<sup>-1</sup> (Fig. 2-3). Overall, both the camelina planted into the plots with and without stover yielded within the typical range of 421-1324 kg ha<sup>-1</sup> in the Upper Midwest (Fig. 2-3; Gesch and Cermak, 2011; Walia et al., 2018; Wittenberg et al., 2020). The differences between treatments were likely a function of seed-soil contact. As a small-seeded crop, camelina does not establish well in environments with heavy residue as they create a physical barrier between camelina seed and the soil surface (Grady and Nleya, 2010; Hunter and Roth, 2010; McVay and Lamb, 2008). This observation was similarly reflected in the camelina ground cover measurements (Table 2-6). At both measurement intervals, the camelina planted into plots where corn stover was removed had more ground cover than plots where corn stover remained. This indicates that camelina was able to establish more readily in plots where corn stover was removed in the autumn and increase its biomass more quickly in the spring following thaw.

Camelina ground cover was also affected by the interaction of corn relative maturity and stover presence (Table 2-6). At both measurement points, the camelina planted after the 82-day corn into plots without corn stover had the greatest cover. This is unsurprising given that the camelina sown under these growing conditions had unobstructed seed-to-soil contact and plenty of autumn growing degree days to allow for

camelina germination and establishment. These circumstances most closely resembled the growing conditions that are typical in camelina-only research studies, and thus, the most optimal scenario for camelina germination and emergence (Berti et al., 2016; Walia et al., 2018). This indicates that there may be number of planting strategies that can be used to optimize camelina performance in scenarios where it is not possible to grow camelina under ideal conditions (*i.e.*, in conjunction with summer annual crops).

#### *Camelina seed quality*

Camelina seed oil content was affected by corn relative maturity and, similar to yield, decreased as corn relative maturity increased (Table 2-4). The camelina seed in this study contained between 395 and 404 g kg<sup>-1</sup> of oil (Table 2-7). These values align with previous camelina research, which has demonstrated seed oil content ranging between 295 and 427 g kg<sup>-1</sup> (Gesch and Cermak, 2011; Gugel and Falk, 2006; Patel et al., 2021; Walia et al., 2018). Camelina seed oil content tends to increase with a later camelina harvest date (Walia et al., 2018). In the context of this experiment, when all camelina treatments were harvested on the same day, an earlier planting date may have provided extra time for seed oil development (Tables 2-2 and 2-7). High seed oil content is a very desirable camelina seed trait; however, it is important to remember that oil yield is a function of both seed oil content and seed yield, meaning that, to maximize oil yield, both parameters need to be taken into account. The first two planting dates had the highest seed oil content while the first planting date had the highest seed yield, suggesting that an earlier planting date corresponded with a higher oil yield (Fig. 2-2; Table 2-7). Indeed, the earliest camelina planting date was estimated to yield 504 L ha<sup>-1</sup> of oil, 22% and 51% more than the second

and third planting dates, respectively (data not shown). These data indicate that a planting date between mid- and late September yielded the maximum volume of camelina oil.

Camelina crude protein was also affected by corn relative maturity and, unlike oil content, increased as corn relative maturity increased (Fig. 2-2; Tables 2-4 and 2-7). The crude protein content ranged between 283 and 292 g kg<sup>-1</sup> and fell within the range measured in other studies on winter camelina, which have reported values between 246 and 384 g kg<sup>-1</sup> (Table 2-7; Gesch et al., 2014; Walia et al., 2018; Anderson et al., 2019; Patel et al., 2021). Changes in camelina crude protein content for each planting date directly corresponded with the changes in oil content (Table 2-7). The first planting date had the greatest amount of time to accumulate seed oil, which is likely the reason that crude protein was lower while the opposite was the case for the last planting date. While oil content is the current focus of camelina production, crude protein may become a future target for camelina production. For example, the potential protein value and relatively low production cost of camelina seed has made camelina an attractive supplement to traditional animal feed (Cherian, 2012). Feeding trials conducted on poultry and dairy production animals have demonstrated promising results when camelina meal replaced a portion of the typical diet (Cherian, 2012; Lawrence et al., 2016). Additionally, camelina has gained traction as a protein-rich meat alternative for human consumption due to its high crude protein and omega-3 fatty acid levels (Kleba and Ismail, 2018). While oil is the primary end-product of camelina at this time, these emerging markets emphasize the importance of and desire for high camelina crude protein content and will likely gain additional interest as production acreage increases.

*Soybean seed yield*

Soybean yield was affected by the corn relative maturity and stover presence as well as their interaction at both sites; only the interaction is presented (Figs. 2-4 and 2-5; Table 2-3). At the Morris site, the control treatment had the highest soybean yield when the stover presence/absence treatments were combined while the top-performing relay-cropped treatments yielded, on average, 2.7 Mg ha<sup>-1</sup> (Fig. 2-4). In comparison, the average soybean yield in Stevens County was 3.2 Mg ha<sup>-1</sup> in 2020 (USDA National Agricultural Statistics Service, 2021a). Only the control soybeans exceeded the average yield in Stevens County (Fig. 2-4; USDA National Agricultural Statistics Service, 2021a). Soybean yield depression is expected when soybean is relay cropped with a winter oilseed for harvest in the same year (Berti et al., 2015; Gesch et al., 2014; Johnson et al., 2017; Ott et al., 2019). At sites in southern and west central Minnesota, camelina yields between 750 and 1500 kg ha<sup>-1</sup> corresponded with a 24-33% reduction in relay-cropped soybean when compared with a soybean monocrop (Gesch et al., 2014; Johnson et al., 2017). This yield depression was even more pronounced as trial locations moved northward; soybean relay cropped with camelina in North Dakota produced 71-89% less seed compared with a soybean monocrop (Berti et al., 2015). Yield depression is one of the very prominent risks of relay cropping and is generally caused by the competition associated with growing two crops in the same space at the same time. Competition for water is generally not an issue in an Upper Midwest camelina-soybean dual cropping system as camelina has a very shallow root structure and is a low water user (Gesch and Johnson, 2015). However, competition for light is a significant issue. Photosynthetically active radiation was not quantified during this experiment, but prior research indicated that between 20 and 50% of the above-canopy light resources were available to soybean when it was relay planted into camelina in late

April or early May (Hoerning et al., 2020; Ott et al., 2019). The ratio between the below and above canopy photosynthetically active radiation began to steadily increase in early to mid-June, which corresponds with the time that camelina typically is at or beyond 50% flowering in Minnesota and fewer resources are directed toward vegetative growth (Gesch and Cermak, 2011; Martinelli and Galasso, 2011; Ott et al., 2019).

The relay-cropped soybean yielded less than the monocrop, but there was a distinct stratification amongst the relay-cropped treatments indicating that some were more favorable for soybean production than others (Fig. 2-4). The highest yielding relay-cropped soybean treatments included those where corn stover remained in place following corn harvest along with the 95 RM x No Stover treatment. Overall, the treatments where the soybean was more successful connected back to the treatments where camelina had relatively poor performance (Figs. 2-2, 2-3, and 2-4; Table 2-6). Stover presence as well as late planting date negatively affected camelina establishment and yield, which, in turn, provided a less competitive environment for the soybean at planting and beyond compared with treatments where camelina had better yields (*i.e.*, an earlier planting date and no stover present) (Figs. 2-2 and 2-3; Table 2-6). While the stratification among corn relative maturities was less pronounced in the interaction than stover presence, it was clear that the soybean relayed into the camelina after the 95 RM corn generally produced higher yields (Fig. 2-4). These camelina plants provided less competition as they were primarily spring-germinated (Table 2-6). Camelina seedlings that emerge in the spring typically produce a smaller plant and are earlier in their lifecycle than those that emerge in the autumn, thus providing less competition at soybean planting (Johnson et al., 2017; Royo-Esnal et al., 2017).

Differences between treatments at the Rosemount site were less pronounced than at the Morris site (Figs. 2-4 and 2-5). The top performing treatments included all but the 90 RM x No stover treatment and had an average soybean yield of 2.4 Mg ha<sup>-1</sup> (Fig. 2-5). In comparison, the average soybean yield in Dakota County was 3.6 Mg ha<sup>-1</sup> in 2020 indicating that soybean yield at the Rosemount site was not particularly competitive, regardless of camelina presence (USDA National Agricultural Statistics Service, 2021a). Two reasons for this may have been a water deficit throughout the soybean growing season as well as weed pressure. In a normal year at the Rosemount site, there are 548 mm of precipitation from May through September (*i.e.*, the primary soybean growing season) (Table 2-1). However, in 2020, there were only 472 mm of precipitation over the same time period with nearly half of the precipitation falling in June and soybean is particularly prone to water stress during its reproductive growth stages (Table 2-1; Eck et al., 1987). All soybean had reached the reproductive phase by 7 July after which there was a water deficit for the remainder of the growing season (data not shown; Table 2-1). Water stress during early reproductive stages has been shown to decrease yield by 9-13% and water stress late in the growing season, like that observed in this study, can reduce yields by 21-88%, depending on duration (Table 2-1; Eck et al., 1987). Similar to the Rosemount site, there was also a water deficit at the very beginning and end of the soybean growing season at the Morris site, but June, July and August had precipitation levels consistent with the 30-year normal (Table 2-1). This may indicate that water stress from mid-summer through the end of the growing season at the Rosemount site negatively affected the soybean yield and may explain the overall differences in yield between the two sites (Figs. 2-4 and 2-5; Table 2-1). Soybean vegetative growth appeared to be unaffected early in the growing

season, as the soybean plants were a similar height to camelina at camelina harvest (personal observation). This further indicates that the soybean yield was reduced due to factors during the reproductive phase of the growing season, which occurred after camelina harvest. It is also important to note that there was significant weed pressure at the Rosemount site following camelina harvest despite weed control measures deployed throughout the summer (Table 2-2). The wide row spacing used for this study to accommodate camelina may have left the soybean more prone to weediness compared with a narrower row spacing (Table 2-2; Wells et al., 2014). These weeds likely competed with soybeans for the limited water resources throughout July when precipitation was scarce, further contributing to depressed yields at harvest (Table 2-1; Eck et al., 1987).

Aside from the differences between the control versus the relay-cropped treatments, one consistent trend between the two experimental sites was stratification by stover treatment (Figs. 2-4 and 2-5). These results were particularly pronounced at the Rosemount site when looking at the lowest-yielding treatments, all of which did not have corn stover in the plots (Fig. 2-5). These treatments yielded an average of  $1.9 \text{ Mg ha}^{-1}$ , or just over half of the Dakota County average (Fig. 2-5; USDA National Agricultural Statistics Service, 2021a). Similar to the Morris site, stover presence itself is likely not the reason for differences in soybean yield despite stover presence having a statistically strong effect on soybean seed yield (Table 2-3). Treatments without corn stover corresponded to treatments where camelina performed better, resulting in lower soybean yields (Figs. 2-3, 2-4, and 2-5; Table 2-6). While corn relative maturity also had a strong significant effect on soybean yield, these results were less visible in the interaction (Fig. 2-5; Table 2-3).

In the case of the Rosemount site, relay-cropping soybean with camelina did not reduce the overall soybean yields compared with the control, suggesting that there may be a number of scenarios that can be used in this cropping system (Fig. 2-5). However, when considering external factors such as the Dakota County average, it is clear that these soybeans did not perform well in general (Fig. 2-5; USDA National Agricultural Statistics Service, 2021a). These results are somewhat similar to a previous study where camelina yields between 500 and 1500 kg ha<sup>-1</sup> corresponded with soybean yields of around 1.5 Mg ha<sup>-1</sup> when the two crops were relay planted (Johnson et al., 2017). The control soybean in the same study yielded between 2.0 and 2.5 Mg ha<sup>-1</sup>. With this in mind, it may be more realistic to consider the combined results from both the Morris and Rosemount sites rather than one site alone to determine a relay-cropping scenario where soybean yield is maximized (Figs. 2-4 and 2-5). Overall, it is clear that leaving stover following corn harvest and later camelina planting dates are more conducive to soybean growth and development.

#### *Soybean seed quality*

Soybean oil content was affected by planting date, but not stover presence or the interaction between planting date and stover presence (Table 2-4). The soybean oil content in this study ranged between 206 and 211 g kg<sup>-1</sup> (Table 2-7). In prior research, relay planted soybean yielded between 208 and 215 g kg<sup>-1</sup> of oil, which largely overlapped with the range of values in this experiment (Gesch et al., 2014; Patel et al., 2021). Despite statistical differences between these treatments, there was little difference in the actual oil content values (Table 2-7). The control and the 82 RM treatments performed similarly to each other while the camelina-soybean relay crop treatments all performed similarly to each other. Soybean oil content can be affected by water stress and high temperatures, both of which

were significant factors during the 2020 growing season. A prior meta-analysis determined that water stress during late reproductive stages, like those observed in this study, reduced soybean oil content by about 35% (Table 2-1; Rotundo and Westgate, 2009). In addition, temperatures were higher-than-average throughout June, July, and August at both sites, which has been demonstrated to reduce oil content by about 15%. Despite this, all soybean oil content values were above average when considering long-term regional data (Rotundo et al., 2016). Soybean crude protein was not affected by planting date, stover presence, or the interaction (Table 2-4). The crude protein averaged  $397 \text{ g kg}^{-1}$  across corn relative maturity treatments (Table 2-7). The typical crude protein range for soybean when relay cropped with camelina falls between 381 and  $404 \text{ g kg}^{-1}$  (Gesch et al., 2014; Patel et al., 2021). This indicates that the values for this study were average when compared with similar experiments.

#### *Aggregate seed yield*

It is evident that there are agronomic trade-offs between the proposed corn-camelina-soybean cropping rotation scenarios (Figs. 2-1, 2-2, 2-3, 2-4, and 2-5). When considered individually, both corn and soybean had reduced yields in treatments that were adapted for camelina integration (Figs. 2-1 and 2-4). However, when the cropping system yield as a whole was taken into account, the control treatments were among the lowest yielding (Fig. 2-6). The control treatment at the Rosemount site yielded  $11.6 \text{ Mg ha}^{-1}$  while the control treatment at the Morris site yielded  $13.1 \text{ Mg ha}^{-1}$ . The 82 RM treatment yielded similarly to the Morris control, indicating that it is not likely to be a viable cropping scenario as the controls acted as a yield baseline in this experiment (Fig. 2-6). While there are clear parameters for evaluating individual crop yields as well as the aggregate yield for

a camelina-soybean relay crop, few studies have quantified the aggregate corn-camelina-soybean yield. One study at sites across the Upper Midwest considered a similar rotation where camelina was interseeded into R6 corn and showed that the camelina-soybean portion of the rotation totaled about 3.0 Mg ha<sup>-1</sup> (Patel et al., 2021). These results were similar to the camelina-soybean yield in the present study, which averaged 3.4 and 3.2 Mg ha<sup>-1</sup> across treatments at the Morris and Rosemount sites, respectively (data not shown). It is important to note that, in the Patel et al. (2021) study, the camelina only yielded 159 kg ha<sup>-1</sup>, meaning that it likely had little impact on the soybean yield. In the present study, camelina yield accounted for a larger proportion of the camelina-soybean aggregate seed yield in all treatments and demonstrated the yield trade-offs of a camelina-soybean relay crop (Figs. 2-2, 2-3, 2-4 and 2-5). However, rather than focus on just one year of the rotation, it should be evaluated in its entirety. In this experiment, the top-performing treatment was the 95 RM treatment followed by the 90 RM treatment, which had total yields of 16.6 and 15.5 Mg ha<sup>-1</sup>, respectively (Fig. 2-6). It is not surprising that the 95 RM treatment was the most successful as this was the most optimal scenario for both the corn and soybean crops (Figs. 2-1, 2-4, and 2-5).

#### *Cropping system economics*

The economic trade-offs of any new cropping rotation are an essential consideration when thinking about cropping system viability. Overall, the value of the corn, camelina, and soybean mirrored the trends observed in their respective yield data and all crops were significant in terms of corn relative maturity (Figs. 2-1, 2-2, 2-3, 2-4; Table 2-5). The 95-day corn had the greatest APV, \$1818 ha<sup>-1</sup>, while the 90- and 82-day relative maturities generated \$152 and \$608 ha<sup>-1</sup> less than their full season counterpart, respectively (Table

2-8). In general, a shorter season corn hybrid yields less than a mid- or full season hybrid, so it is unsurprising that the short season hybrid in this study also generated a lower APV (Table 2-8; Assefa et al., 2016). However, it is important to reiterate that the yield of the 82-day corn at the Morris site suffered due to bird predation and that, because of this, both the yield and APV were lower than was expected for this relative maturity (Fig. 2-1; Table 2-8). In a different year, the reduced viability of the 82-day corn may not be as much of an issue when choosing a corn hybrid within this cropping system.

The 95-day corn hybrid was, economically-speaking, the best option out of the hybrids grown in this trial, but the impact on the camelina double crop also needs to be taken into consideration (Table 2-8). The mid-October camelina planting date that corresponded with the harvest of the 95-day hybrid negatively affected autumn camelina establishment and seed yield the following spring (Fig. 2-2; Tables 2-2 and 2-5). This was reflected in the value of the 95 RM treatment, which was \$524 ha<sup>-1</sup>, the lowest of the camelina APVs (Table 2-8). Therefore, a safer recommendation for the corn hybrid within the context of a corn-camelina double crop is the 90-day hybrid. While the 90-day hybrid had a decrease in yield and APV compared with the 95-day relative maturity, it did not have as much of a negative impact on the proceeding camelina crop (Figs. 2-1 and 2-2; Tables 2-5 and 2-8). The camelina planted after the 90-day corn yielded an APV of \$811 ha<sup>-1</sup>, significantly less than the 82 RM treatment, but significantly more than the 95 RM treatment (Table 2-8). The top performing soybean treatment was the control at both sites (Table 2-8). At the Morris site, the relay-cropped treatments all performed similarly to each other. At the Rosemount site, the 82 and 95 RM treatments performed similarly to each other while the 90 RM treatment had the lowest APV.

It is clear based on this data that finding balance will be the key to cropping system viability, which also means that the top-performing treatment for one crop may not be the best option due to trade-offs in profitability with other crops in the rotation. Overall, the 90 and 95 RM treatments had the highest net APV, which included the value of the crops as well as the estimated cost of production (Table 2-8). At the Morris site, the 90 and 95 RM treatments had net APVs of \$1851 and \$1792 ha<sup>-1</sup>, respectively, while the 90 and 95 RM treatments at the Rosemount site were valued as \$1631 and \$1628 ha<sup>-1</sup>, respectively. The 82 RM treatment also performed similarly to the other relay cropped treatments at the Rosemount site at \$1552 ha<sup>-1</sup>. These net APVs indicate that the control and the 82 RM treatment, in the case of the Morris site, were less profitable than the other treatments. Instead, a cropping rotation that includes a 90- or 95-day corn hybrid double-cropped with camelina and then relay cropped with soybean appeared to yield the most profitable rotation when considering the corn relative maturity treatment alone.

However, this study did not solely focus on corn relative maturity, stover presence significantly affected both the camelina and soybean APVs (Table 2-5). For camelina, treatments with stover removed were valued at \$905 ha<sup>-1</sup> compared with \$697 ha<sup>-1</sup> for the treatments where the corn stover remained in the plot (Table 2-8). In contrast, the soybean APV in plots with stover present yielded a significantly higher APV than plots with the stover removed (Table 2-8). This represents yet another trade-off within this cropping rotation that is not as easily resolved as corn relative maturity. The net APVs were not significantly affected by stover presence, so it is difficult to draw conclusions about how stover removal affected the cropping system as a whole (Table 2-5). However, the trade-offs within the camelina-soybean relay crop can still be taken into consideration. The

camelina value when stover was removed yielded 30% more than when stover was present, in comparison, the difference between soybean treatments was only 9% at the Morris site and 17% different at the Rosemount site. Tentatively, removing stover may have had a lower economic impact on soybean than keeping the stover did on camelina based on these calculations. The estimated value of camelina meal and oil (using canola prices as a proxy) is higher than for soybean, so there may be additional economic advantages to maximizing camelina yield as the markets become fully developed (Canola Council of Canada, 2021; USDA Foreign Agricultural Service, 2022, 2020, 2019, 2018). However, the process of removing corn stover adds an extra field activity for growers at a point in the season when time is critical and in short supply (Roesch-McNally et al., 2017). For this reason, the additional time, labor cost, and implements required to efficiently and effectively remove corn stover may negate any benefits that arise in conjunction with stover removal.

The soybean APV was also affected by the interaction of corn relative maturity and stover presence. The soybean APV was highest for the plots that did not include camelina at the Morris site, regardless of stover presence (Table 2-8). These plots had an average APV of \$1683 ha<sup>-1</sup>. In comparison, the highest yielding relay-cropped soybean treatments yielded \$1113 ha<sup>-1</sup>, representing a 34% decrease in APV. Prior research that focused on a soybean-camelina relay crop had similar results where there was an average APV decrease of 31% between a soybean mono and relay crop, indicating that this difference in value is somewhat typical for this cropping system in Minnesota (Gesch et al., 2014). Due to the low control yields at the Rosemount site, the control plots as well as the plots that included corn stover had the highest APVs, which averaged \$1039 ha<sup>-1</sup>. This further indicated the negative impact that stover removal had on soybean yield (Figs. 2-4 and 2-5; Table 2-8).

Neither the camelina or the net APVs at either site were affected by the corn relative maturity and corn stover interaction.

Note that there are limitations to these results. These values do not account for labor throughout crop production, transportation, and post-harvest processing. If these costs were taken into account, there would be a steep reduction in the APVs presented here, with some values potentially representing a loss rather than a profit. It is also important to note that the camelina APVs were calculated using the 2018-2021 prices for canola oil and meal rather than the actual values for camelina oil and meal (Canola Council of Canada, 2021; USDA Foreign Agricultural Service, 2022, 2020, 2019, 2018). These values may shift in the future as the markets for camelina become more established in the United States, but for the time being serve as the best market proxy.

## **2.5. CONCLUSIONS**

While the final agronomic and economic results do not clearly demonstrate an optimal way to integrate winter camelina into a corn-soybean rotation, they do indicate that including camelina in rotation is viable compared with the corn-soybean control. Corn relative maturity had a strong effect on each individual crop as well as the aggregate yield and economics and will require the most consideration in future studies. The middle ground between corn and camelina yield maximization and profitability was the 90-day corn hybrid while stover removal appeared to be most beneficial for camelina and soybean establishment and yield despite the timing and cost. As this cropping system develops, these values will continue to shift until complete best management practices are established. Future research directions based on this work could include additional site-

years of the same experiment, an expansion of the corn relative maturities tested, and novel camelina seeding strategies to ensure better establishment in stover.

There are inherent risks and trade-offs associated with adding a winter annual crop, like camelina, to the corn-soybean cropping rotation. Yield reduction is a chief concern and both the corn and soybean seed yields were negatively affected by the addition of camelina in the present experiment. This highlights the importance of balance: in order to truly integrate camelina into the corn-soybean rotation, the entire system must shift. In the instance of corn, this means a shorter growing season to allow for fall camelina germination and development, and for soybean, this means seeding into an existing stand of camelina. While these changes do not reflect the standard best management practices for either corn or soybean, they may represent a new set of best management practices for when a winter oilseed is involved in the cropping rotation. These changes also necessitate a mental shift as it is unlikely that any single crop will be maximized in terms of yield or economic return in this rotation. The goal should instead be to maximize the rotation as a whole, an idea that will be realized after two growing seasons rather than after a single growing season.

## **2.6. TABLES AND FIGURES**

Table 2-1. Mean monthly air temperature and cumulative precipitation over the 2019 and 2020 growing seasons and the 30-year normal (1991-2020) for the Morris and Rosemount, MN experimental sites.

| Crop     | Year | Month | Morris, MN  |         |               |        | Rosemount, MN |        |               |        |
|----------|------|-------|-------------|---------|---------------|--------|---------------|--------|---------------|--------|
|          |      |       | Temperature |         | Precipitation |        | Temperature   |        | Precipitation |        |
|          |      |       | Mean        | Normal† | Total         | Normal | Mean          | Normal | Total         | Normal |
|          |      |       | °C          |         | mm            |        | °C            |        | mm            |        |
| Corn     | 2019 | May   | 11.8        | 13.5    | 106           | 79     | 11.6          | 14.0   | 173           | 110    |
|          |      | June  | 19.8        | 19.3    | 79            | 111    | 19.9          | 19.6   | 76            | 124    |
|          |      | July  | 22.2        | 21.3    | 111           | 108    | 22.0          | 21.7   | 180           | 115    |
|          |      | Aug   | 19.5        | 19.9    | 137           | 88     | 17.5          | 20.4   | 94            | 113    |
|          |      | Sept  | 17.1        | 15.5    | 178           | 68     | 17.6          | 16.2   | 146           | 87     |
|          |      | Oct   | 5.9         | 7.5     | 79            | 62     | 6.8           | 8.7    | 109           | 73     |
|          |      | Nov   | -2.0        | -1.1    | 9             | 25     | -2.1          | 0.3    | 27            | 43     |
|          |      | Dec   | -8.2        | -8.6    | 27            | 19     | -6.6          | -7.1   | 35            | 31     |
| Camelina | 2020 | Jan   | -9.9        | -12.3   | 14            | 18     | -7.7          | -10.7  | 58            | 24     |
|          |      | Feb   | -9.5        | -10.1   | 3             | 19     | -8.5          | -8.3   | 15            | 23     |
|          |      | Mar   | 0.1         | -2.6    | 10            | 31     | 1.1           | -1.0   | 35            | 46     |
|          |      | Apr   | 5.2         | 5.8     | 38            | 57     | 6.1           | 7.1    | 8             | 79     |
|          |      | May   | 13.3        | 13.5    | 27            | 79     | 13.6          | 14.0   | 57            | 110    |
|          |      | June  | 22.0        | 19.3    | 112           | 111    | 21.1          | 19.6   | 228           | 124    |
|          |      | July  | 22.8        | 21.3    | 116           | 108    | 23.1          | 21.7   | 58            | 115    |
|          |      | Aug   | 21.3        | 19.9    | 71            | 88     | 21.3          | 20.4   | 101           | 113    |
| Soybean  | 2020 | Sept  | 15.0        | 15.5    | 18            | 68     | 14.8          | 16.2   | 28            | 87     |
|          |      | Oct   | 4.5         | 7.5     | 32            | 62     | 4.9           | 8.7    | 77            | 73     |

† The 30-year air temperature and cumulative precipitation averages from 1991-2020 were obtained from the West Central Research and Outreach Center in Morris, MN for the Morris research site (approximately 18 km from the study location) and were available for the Rosemount Research and Outreach Center for the Rosemount research site.

Table 2-2. Summary of field management practices for corn, camelina, and soybean at Morris and Rosemount, MN over the 2019 and 2020 growing seasons.

|   | Management activity                         | Morris, MN                   | Rosemount, MN               |              |
|---|---|------------------------------|-----------------------------|--------------|
| Corn                                      | Preceding crop                              | Soybean                      | Soybean with rye cover crop |              |
|   | Field preparation                           | Chisel plowed                | Chisel plowed and disked    |              |
|   | Fertilization (kg ha <sup>-1</sup> N-P-K-S) | 168-67-67-11                 | 157-117-135-20              |              |
|   | Planting date                               | 6 May 2019                   | 7 May 2019                  |              |
|   | Planting rate (seeds ha <sup>-1</sup> )     | 84,757                       | 87,969                      |              |
|   | Row spacing (cm)                            | 76                           | 76                          |              |
|   | Herbicide                                   | Glyphosate                   | Glyphosate                  |              |
|   | Date  | 6 and 18 June 2019           | 23 May and 12 June 2019     |              |
|   | Herbicide                                   | Bromoxynil                   | ---                         |              |
|   | Date  | 18 and 27 July 2019          | ---                         |              |
|   | Hand weeding                                | ---                          | July 2019                   |              |
|   | Harvest date                                |                              |                             |              |
|   | DKC 32-12 (82 day)                          | 24 Sept 2019                 | 26 Sept 2019                |              |
|   | DKC 40-77 (90 day)                          | 8 Oct 2019                   | 9 Oct 2019                  |              |
|   | DKC 45-65 (95 day)                          | 18 Oct 2019                  | 18 Oct 2019                 |              |
|   | Harvest method                              | Combine harvest              | Hand harvest                |              |
|   | Stover removal                              | Lely weeder                  | Hand raked                  |              |
|   | Camelina                                    | Planting date by corn hybrid |                             |              |
|   |   | DKC 32-12 (82 day)           | 24 Sept 2019                | 26 Sept 2019 |
| DKC 40-77 (90 day)                        |   | 8 Oct 2019                   | 9 Oct 2019                  |              |
| DKC 45-65 (95 day)                        |   | 18 Oct 2019                  | 18 Oct 2019                 |              |
| Planting rate (kg ha <sup>-1</sup> )      |   | 11.5                         | 11.2                        |              |
| Row spacing (cm)                          |   | 19 with skip row every 76    | 19 with skip row every 76   |              |
| Fertilization (kg ha <sup>-1</sup> N-P-K) |   | 56-34-34                     | 56-34-34                    |              |
| Harvest date                              |   | 6 July 2020                  | 6 July 2020                 |              |
| Harvest method                            | Combine harvest                             | Hand harvest                 |                             |              |
| Soybean                                   | Variety                                     | NK S11-E3                    | AG20X                       |              |
|   | Maturity group                              | 1.1                          | 2.0                         |              |

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|   |              |                     |
|---|--------------|---------------------|
| Planting date (by corn hybrid)          |              |                     |
| DKC 32-12 (82 day)                      | 7 May 2020   | 8 May 2020          |
| DKC 40-77 (90 day)                      | 7 May 2020   | 8 May 2020          |
| DKC 45-65 (95 day)                      | 7 May 2020   | 20 May 2020         |
| Planting rate (seeds ha <sup>-1</sup> ) | 432,434      | 380,542             |
| Row spacing (cm)                        | 76           | 76                  |
| Herbicide                               | Glufosinate  | Glyphosate          |
| Date                                    | 23 July 2020 | 10 and 31 July 2020 |
| Hand weeding                            | ---          | July 2020           |
| Harvest date                            | 6 Oct 2020   | 30 Oct 2020         |

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Table 2-3. Mixed effects model analysis of variance for crop seed yield by corn relative maturity (RM), stover presence (S), and their interaction (RM x S).

| Fixed effects† | Soybean |          |        |           |           |
|----------------|---------|----------|--------|-----------|-----------|
|                | Corn    | Camelina | Morris | Rosemount | Aggregate |
| RM             | ***‡    | ***      | ***    | ***       | ***       |
| S              | ---     | **       | *      | ***       | ns        |
| RM x S         | ---     | ns§      | ***    | *         | ns        |

† Maximum-likelihood comparisons guided model simplification.

‡ \*, \*\*, and \*\*\* refers to parameters with p-values of 0.05, 0.01, and 0.001, respectively, for a given fixed effect.

§ ns refers to parameters that were not significant for the given fixed effect.

Table 2-4. Mixed-model analysis of variance of camelina and soybean seed quality by corn relative maturity (RM), stover presence (S), and their interaction (RM x S).

| Fixed effects† | Camelina      |     | Soybean       |     |
|----------------|---------------|-----|---------------|-----|
|                | Crude protein | Oil | Crude protein | Oil |
| RM             | *‡            | *   | ns            | *** |
| S              | ns§           | ns  | ns            | ns  |
| RM x S         | ns            | ns  | ns            | ns  |

† Maximum-likelihood comparisons guided model simplification.

‡ \*, \*\*, and \*\*\* refers to parameters with p-values of 0.05, 0.01, and 0.001, respectively, for a given fixed effect.

§ ns refers to parameters that were not significant for the given fixed effect.

Table 2-5. Mixed effects model analysis of variance for approximate processed value by corn relative maturity (RM), stover presence (S), and their interaction (RM x S).

| Fixed effects† | Morris |          |         |           | Rosemount |           |
|----------------|--------|----------|---------|-----------|-----------|-----------|
|                | Corn   | Camelina | Soybean | Aggregate | Soybean   | Aggregate |
| RM             | ***‡   | ***      | ***     | ***       | ***       | ***       |
| S              | ---    | **       | **      | ns        | ***       | ns        |
| RM x S         | ---    | ns§      | ***     | ns        | ***       | ns        |

† Maximum-likelihood comparisons guided model simplification.

‡ \*, \*\*, and \*\*\* refers to parameters with p-values of 0.05, 0.01, and 0.001, respectively, for a given fixed effect.

§ ns refers to parameters that were not significant for the given fixed effect.

Table 2-6. Camelina ground cover in the autumn and spring by corn relative maturity, stover presence, and their interaction. Values within a column and treatment type that share a letter are not statistically significant from each other based on Tukey's HSD ( $P < 0.05$ ).

| Treatment         | Ground cover |        |
|-------------------|--------------|--------|
|                   | Autumn       | Spring |
|                   | %            |        |
| 82 RM             | 0.44a        | 4.84a  |
| 90 RM             | 0.14b        | 0.65b  |
| 95 RM             | 0.01c        | 0.16b  |
| Stover            | 0.08b        | 0.69b  |
| No stover         | 0.28a        | 2.55a  |
| 82 RM x Stover    | 0.18bc       | 2.09b  |
| 82 RM x No stover | 0.79a        | 6.56a  |
| 90 RM x Stover    | 0.06cd       | 0.39cd |
| 90 RM x No stover | 0.22b        | 0.87bc |
| 95 RM x Stover    | 0.01d        | 0.08d  |
| 95 RM x No stover | 0.01d        | 0.24cd |

Table 2-7. Camelina and soybean seed oil content and crude protein by corn relative maturity. Values within a column that share a letter are not statistically significant from each other based on Tukey's HSD ( $P < 0.05$ ). Values within a column that do not have letters were not significantly different from each other. All values are presented on a dry matter basis.

| Treatment | Camelina           |               | Soybean            |               |
|-----------|--------------------|---------------|--------------------|---------------|
|           | Oil                | Crude protein | Oil                | Crude protein |
|           | g kg <sup>-1</sup> |               | g kg <sup>-1</sup> |               |
| Control   | ---                | ---           | 211a               | 397           |
| 82 RM     | 404a               | 283b          | 208ab              | 394           |
| 90 RM     | 402ab              | 285ab         | 206b               | 400           |
| 95 RM     | 395b               | 292a          | 207b               | 398           |

Table 2-8. The approximate processed value (APV) of corn, camelina, and soybean and net aggregate APV by corn relative maturity, stover presence, and the interaction between the two main effects. Values within a treatment type and column that share a letter are not statistically significant from each other based on Tukey's HSD ( $P < 0.05$ ). Values within a treatment type and column that do not have letters were not significantly different from each other.

| Treatment           | Corn  | Camelina | Morris              |       | Rosemount |       |  |
|---------------------|-------|----------|---------------------|-------|-----------|-------|--|
|                     |       |          | Soybean             | Net   | Soybean   | Net   |  |
|                     |       |          | \$ ha <sup>-1</sup> |       |           |       |  |
| Control             | 1210c | ---      | 1683a               | 1603b | 1095a     | 1005b |  |
| 82 RM               | 1210c | 1051a    | 973b                | 1608b | 922b      | 1552a |  |
| 90 RM               | 1666b | 811b     | 1023b               | 1851a | 792c      | 1631a |  |
| 95 RM               | 1818a | 524c     | 1101b               | 1792a | 937b      | 1628a |  |
| Stover              | ---   | 697b     | 1260a               | 1704  | 1020a     | 1505  |  |
| No stover           | ---   | 905a     | 1148b               | 1729  | 852b      | 1422  |  |
| Control x Stover    | ---   | ---      | 1606a               | 1533  | 1090a     | 998   |  |
| Control x No stover | ---   | ---      | 1760a               | 1672  | 1098a     | 1011  |  |
| 82 RM x Stover      | ---   | 878      | 1115bc              | 1538  | 1012a     | 1476  |  |
| 82 RM x No stover   | ---   | 1223     | 866d                | 1660  | 833b      | 1627  |  |
| 90 RM x Stover      | ---   | 756      | 1134b               | 1911  | 992a      | 1769  |  |
| 90 RM x No stover   | ---   | 859      | 912cd               | 1791  | 524c      | 1447  |  |
| 95 RM x Stover      | ---   | 464      | 1147b               | 1792  | 1003a     | 1649  |  |
| 95 RM x No stover   | ---   | 593      | 1055bcd             | 1792  | 870b      | 1608  |  |

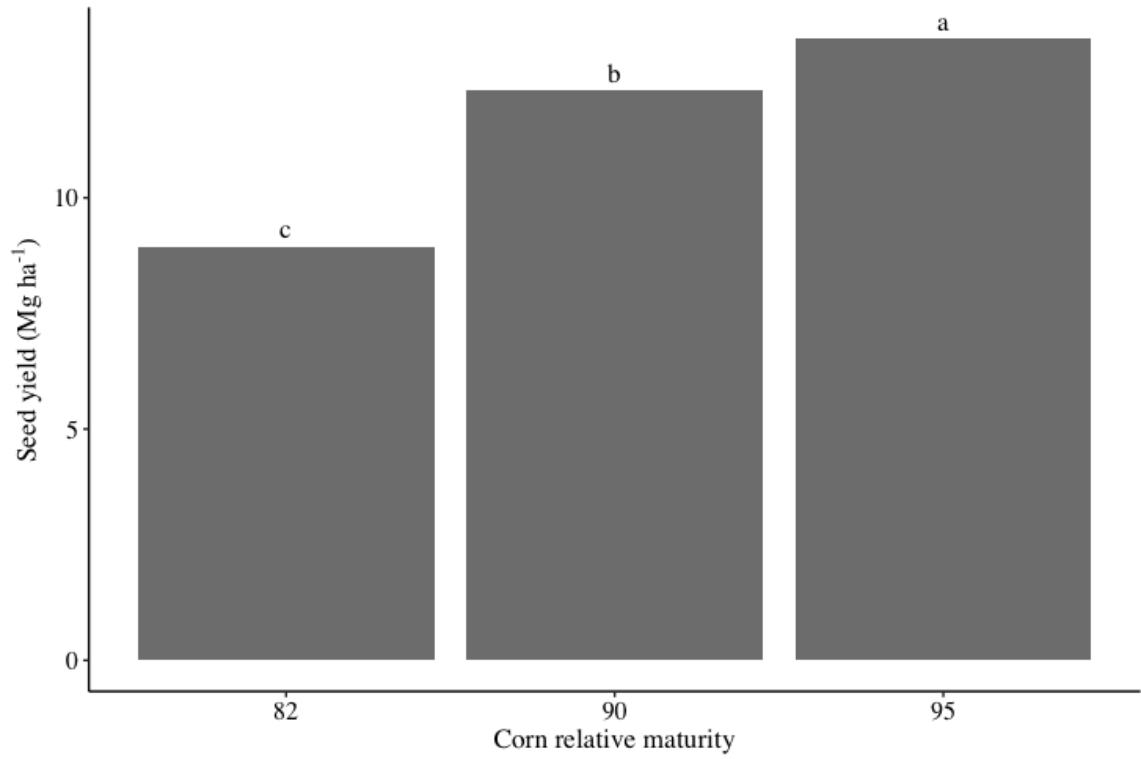


Figure 2-1. Corn yield by corn relative maturity. Relative maturities that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ).

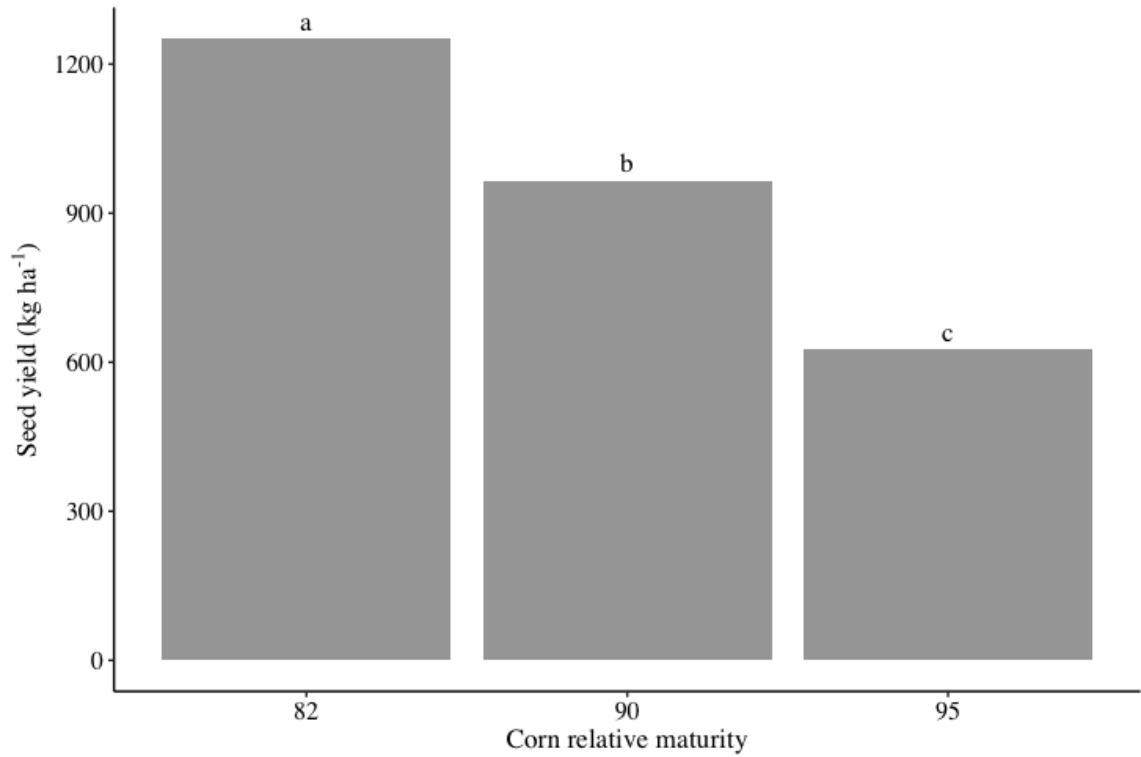


Figure 2-2. Camelina yield by corn relative maturity. Relative maturities that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ).

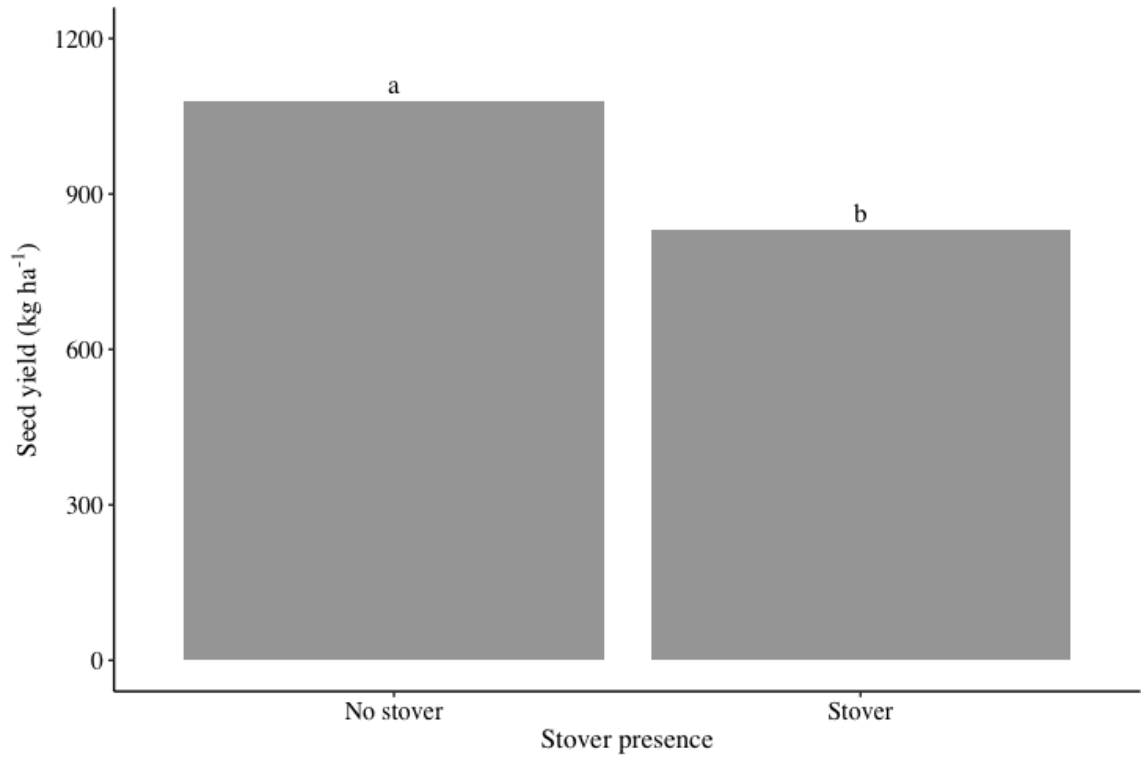


Figure 2-3. Camelina yield by stover presence. Relative maturities that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ).

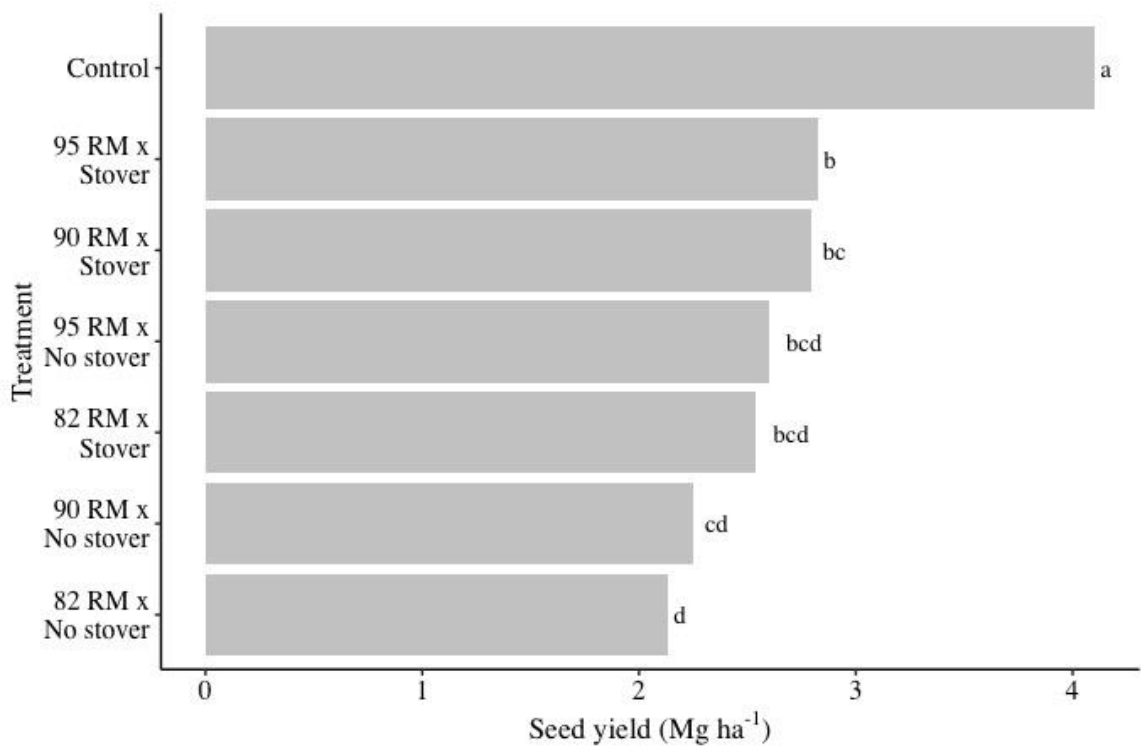


Figure 2-4. Soybean yield by the interaction of corn relative maturity and stover presence for the Morris site. Treatments that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ). Soybean control treatments were not statistically significant from each other and were combined for presentation.

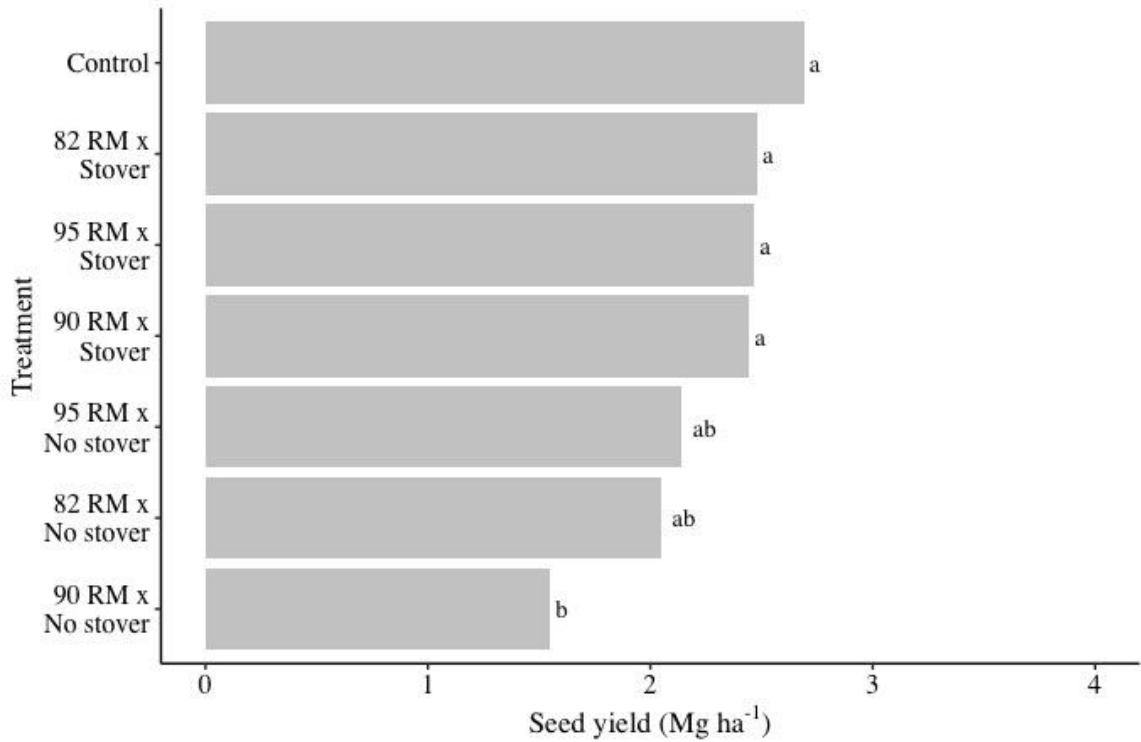


Figure 2-5. Soybean yield by the interaction of corn relative maturity and stover presence for the Rosemount site. Treatments that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ). Soybean control treatments were not statistically significant from each other and were combined for presentation.

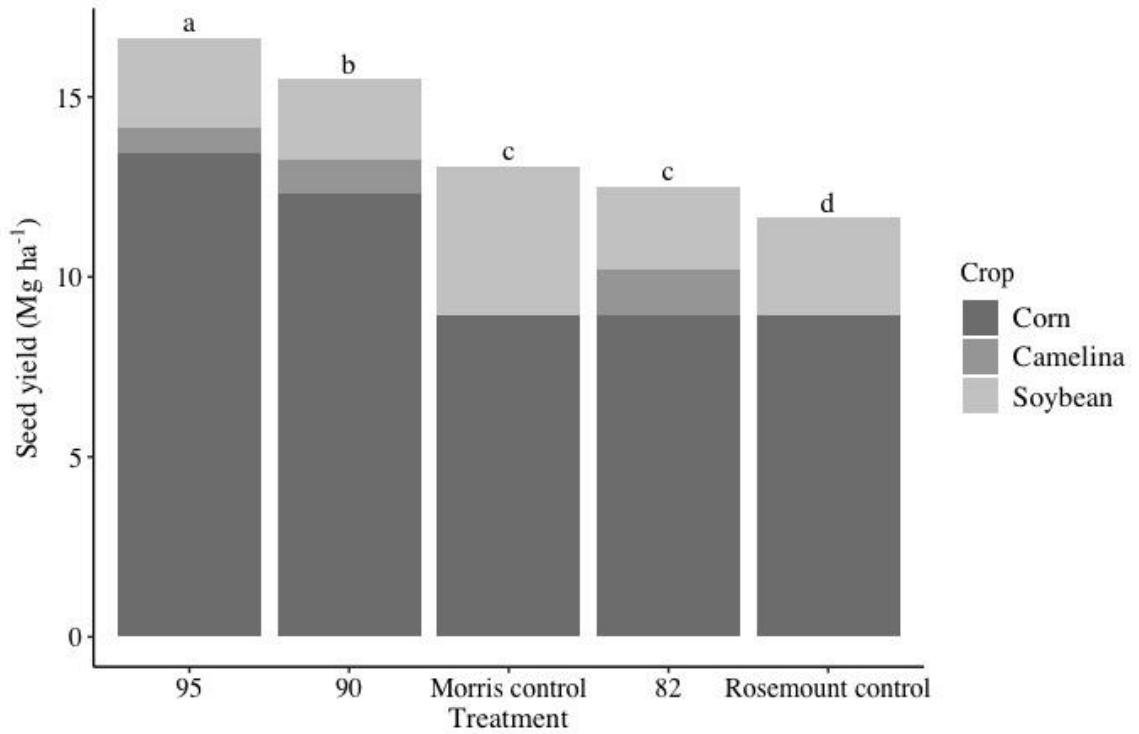


Figure 2-6. Aggregate seed yield by corn relative maturity. Control plots were split by maturity group (representing the two locations). Treatments that share a letter of significance are not statistically different from each other based on Tukey's HSD ( $P < 0.05$ ). Corn relative maturity treatments were not significantly different between locations and were combined for presentation. Control treatments were not statistically significant from each other and were combined for presentation.

### **3. CAMELINA IMPACT ON SOIL NUTRIENTS, CARBON DIOXIDE EFFLUX, AND SOIL CARBON WITHIN THE CORN-SOYBEAN ROTATION.**

#### **3.1. SUMMARY**

Corn (*Zea mays* L.) and soybean (*Glycine max* [L.] Merr) are the dominant agricultural crops in the Upper Midwest, but are associated with a fallow period between the autumn and spring, which can result in loss of key nutrients to local waterways. Nutrient loss can be mitigated by integrating a winter annual, like camelina (*Camelina sativa* L.), into the cropping rotation. Planting camelina following corn is challenging as camelina does not readily establish in a high-residue environment. Stover can be removed from the soil surface, but this practice can result in a carbon deficit. Thus, the objectives of this study were to quantify changes in nitrogen and phosphorus in the soil profile over time; observe soil carbon dioxide (CO<sub>2</sub>) flux throughout the camelina growing season compared with corn-soybean best management controls; and understand the role of camelina biomass as a carbon source. This experiment was conducted over the 2019 and 2020 growing seasons in Morris and Rosemount, MN, USA and followed a corn-camelina-soybean rotation. Over time, phosphorus increased in the topsoil between autumn and spring and nitrate decreased in the top- and subsoil between the spring and summer, indicating biomass mineralization and plant nitrate use, respectively. CO<sub>2</sub> emissions varied little between treatments over the spring-portion of the camelina growing season, but plots with camelina did have lower CO<sub>2</sub> efflux after rainfall events. Total carbon did not change over the period of study, indicating that loss was not a significant factor over the duration of this experiment. Future research should include longer-term experimentation to better understand the nutrient cycling

dynamics, especially carbon, for the corn-camelina-soybean system while future greenhouse gas studies should deploy automatic chambers and measure additional gases.

### **3.2. INTRODUCTION**

Corn and soybean are the dominant agricultural crops in the Upper Midwest region of the USA. Over the 2020 growing season in Minnesota alone, 6 million hectares were dedicated to corn and soybean production, accounting for almost 60% of the state's farmed acreage (USDA National Agricultural Statistics Service, 2021c). While these economically-important crops spatially occupy much of the agricultural landscape each year, there are temporal gaps with no living cover from late autumn through early spring. These gaps are often associated with nutrient loss due to the lack of vegetative cover and can result in nutrient loading in local waterways (Heggenstaller et al., 2008; Wall et al., 2013). Nutrient loss is problematic as surface waters with high levels of nitrogen, particularly the nitrate ( $\text{NO}_3^-$ ) form, are associated with aquatic life toxicity; downstream hypoxia, particularly in the Gulf of Mexico; and negative health outcomes for those who consume the nitrogen-rich water (Wall et al., 2013). One way to diminish these detrimental effects is by ensuring that there is living cover on agricultural land in April, May, and June when nitrogen loss to groundwater is the greatest (Randall and Vetsch, 2005). Temporal intensification, a practice where multiple crops are grown on the same piece of land within a single growing season makes it possible to establish living cover in the fall, which can then protect the landscape during the vulnerable spring period with minimal displacement of the pre- and proceeding summer annual crops (Heaton et al., 2013).

Two common temporal intensification strategies are double cropping, where a second crop is planted just after the first crop is harvested, and relay cropping, where a second crop is planted before the first crop is harvested. The most common crops recommended in Minnesota include winter rye (*Secale cereale* L.), triticale (x *Triticosecale* Wittmack), and barley (*Hordeum vulgare* L.) as they can reliably be established in September and October (Midwest Cover Crops Council, 2018; University of Minnesota Extension, 2021). While each of these species can be harvested for grain, they are typically terminated in the vegetative stage in order to ensure timely planting of the following summer annual (Sustainable Agriculture Research & Education program, 2012). This means that there are no marketable products harvested from these winter crops; they act as cover crops rather than cash crops. Cover crops can provide the environmental services that are critically needed within the corn-soybean rotation including the protection of local waterways from soil erosion and nutrient runoff. However, the lack of near-term profitability has hindered cover crop adoption across the United States (Crop Technology Information Center, 2020). Within the Upper Midwest, the cover crop adoption rate ranges between 1 and 10%, indicating that the majority of agricultural land is without cover during the fallow season (Wallander et al., 2021). This presents an opportunity for alternative winter crops that can fulfill essential gaps in environmental stewardship within the corn-soybean rotation as well as expand economic opportunities for growers using techniques that minimally disrupt summer annual production.

Recent genetic, breeding, and agronomic developments have given rise to winter-hardy annual oilseed species that can fulfill both the environmental and economic needs of corn and soybean farmers (Berti et al., 2016; Cubins et al., 2019). One such species is

camelina. Camelina is an annual Brassicaceae that originated in southeast Europe and southwest Asia, but has naturalized to many environments across the globe (Berti et al., 2016). The winter ecotype of camelina can survive the harsh winter conditions characteristic of the Upper Midwest and completes its lifecycle early in the summer, leaving ample time for the growth and development of a summer annual crop (Berti et al., 2017; Gesch et al., 2014; Walia et al., 2018). However, what sets camelina apart from the typically-recommended cover crop species is that its seed produces an oil with multiple edible and industrial end uses (Berti et al., 2016; Lawrence et al., 2016; Natelson et al., 2015; Woyengo et al., 2016). Despite the increase in camelina research over the past decade, there are still many questions surrounding the management strategies and environmental impact of integrating camelina into the corn-soybean rotation (Berti et al., 2016). It was previously established that camelina can reduce the amount of  $\text{NO}_3^-$  vulnerable to loss between autumn and early spring, but these results focused only on the camelina-soybean portion of the cropping rotation (Johnson et al., 2017; Weyers et al., 2019). In both of these studies camelina was planted following a small grain, omitting corn entirely. Thus, further research where corn is included in the cropping rotation directly preceding camelina is necessary to fully understand the ability of camelina to reduce nutrient loss within the corn-soybean system.

Additionally, camelina is a small seeded crop and does not establish well in high-residue environments like that following corn harvest (Grady and Nleya, 2010; Hunter and Roth, 2010; McVay and Lamb, 2008). While corn stover can be removed before camelina is planted to better ensure successful stand establishment, removing this source of carbon and ground cover may negatively impact soil health. Stover removal leaves the soil more

susceptible to erosion and decreases the available carbon inputs that can be used to build and maintain soil organic carbon (Corning et al., 2016; Kim et al., 2009; Wilhelm et al., 2004, 1986). Corn stover removal is also associated with changes in carbon dioxide (CO<sub>2</sub>) emissions from the soil, which represents a major avenue of carbon loss (Corning et al., 2016). One study simulating stover removal in a continuous corn system concluded that stover removal rate did not have an appreciable effect on soil CO<sub>2</sub> emissions, but suggested that overall carbon loss was higher in plots where stover was removed (O'Brien et al., 2020). Cover crops have shown promise as a method to reduce the impact of stover removal in the corn-soybean rotation by introducing new carbon to the system in the form of biomass, but studies have not yet focused on the use of winter oilseeds, like camelina, as a way to ameliorate the losses associated with stover removal (Blanco-Canqui et al., 2014; Osborne et al., 2014; Sindelar et al., 2017). Based on the gaps in prior research, the objectives of this study were to 1) quantify nutrient changes in the soil profile under corn-soybean treatments with and without camelina and with and without corn stover; 2) observe soil CO<sub>2</sub> flux throughout the camelina growing season compared with corn-soybean best management controls; and 3) understand the role of camelina biomass in the carbon cycle when corn stover is removed.

### **3.3. MATERIALS AND METHODS**

#### *Cultural practices*

This experiment was conducted during the 2019 and 2020 growing seasons at the USDA-ARS Swan Lake Research Farm near Morris, MN (45°41'12" N 95°48'12" W) and at the University of Minnesota Rosemount Research and Outreach Center in Rosemount,

MN (44°42'35" N 93°04'18" W). The soil at the Morris site over both growing seasons was classified as a Barnes loam soil (fine-loamy, mixed, superactive, frigid Calcic Hapludoll) and the soil at the Rosemount site was classified as a Waukegan silt loam (fine-silty over sand-skeletal, mixed, superactive, mesic Typic Hapludoll) over both growing seasons. Monthly precipitation and mean air temperature were recorded by weather stations at each site (Table 3-1). The 30-year air temperature and precipitation averages from 1991-2020 were obtained from sites in close proximity to the research sites (National Centers for Environmental Information, 2021). Thirty-year averages from the West Central Research and Outreach Center in Morris, MN were used for the Morris research site; the West Central Research and Outreach center is approximately 18 km from the study location. Thirty-year averages were available for the Rosemount Research and Outreach Center.

#### *Agronomic management*

A full description of the agronomic and field management practices for this experiment can be found in Table 2-2. The experimental design was a split-plot randomized complete block design with four replicates. The main plot treatment was corn hybrid. The split plot treatment was the presence or absence of corn stover following corn harvest. The Morris and Rosemount sites were prepared and planted with corn on 6 and 7 May 2019, respectively. Three relative maturities of corn were planted: an 82-day hybrid (Dekalb 'DKC 32-12'); a 90-day hybrid (Dekalb 'DKC 40-77'); and 95-day hybrid (Dekalb 'DKC 45-65'). Within each replicate, there were four plots of 82-day corn, two plots of 90-day corn, and two plots of 95-day corn. Corn harvest was staggered according to the maturation of each relative maturity. The 82-, 90-, and 95-day hybrids were harvested in late September, early October, and mid-October, respectively. Following bulk harvest, stover

was removed from half of the plots, so that, within each replicate, there were two 82-day corn plots with and without stover and one plot with and without corn stover for both the 90- and 95-day corn hybrids. Stover was removed using a Lely weeder (Lely Turf Products, Pella, IA) at the Morris site and hand raked at the Rosemount site. One set of the 82-day hybrid plots (*i.e.*, one with and one without stover) were used as the experimental control. The rest of the plots were no-till planted with camelina (cultivar Joelle) on 24 September, 8 October, and 18 October at the Morris site and on 26 September, 9 October, and 18 October at the Rosemount site following the 82-, 90-, and 95-day corn hybrids, respectively. Fertilizer was broadcast by hand on the camelina plots at a rate of 56-34-34 and 79-34-34 kg ha<sup>-1</sup> of N-P-K in April 2020 at the Morris and Rosemount sites, respectively, after the soil had thawed. Soybean was relay planted into camelina with a no-till drill prior to camelina bolting. All plots were planted with soybean at the Morris site on 7 May 2020. Rosemount had two soybean planting dates due to delayed camelina maturation; the control plots and the first two camelina planting dates were planted with soybean on 8 May and soybean was no-till planted into the final camelina planting date on 20 May. Camelina was harvested from both sites on 6 July 2020. Soybean was combine harvested on 6 October 2020 in Morris and on 30 October 2020 in Rosemount.

#### *In-season measurements*

Camelina canopy cover was assessed two weeks after the final camelina planting date in November 2019 and again in April 2020 following spring thaw. Canopy cover was measured using the Canopeo app (Oklahoma State University, Stillwater, OK). Canopy cover was measured in a 2000 cm<sup>2</sup> and a 7600 cm<sup>2</sup> area at the Morris and Rosemount sites, respectively. Weekly CO<sub>2</sub> efflux measurements were taken with a LI-6400-09 Portable

Photosynthesis System (LI-COR Biosciences, Lincoln, NE) between April and July 2020 at the Rosemount site. Three planting scenarios were chosen for these measurements due to time limitations of using the instrument: the two control plots (82-day corn with and without stover) and the 82-day corn with camelina, but without stover. These plots were chosen to simulate the best management practices for grain corn, silage corn, and the best-case scenario for camelina under a double-cropping scenario with corn, respectively. Polyvinyl chloride (PVC) support collars were cut to the specifications outlined in the LI-6400-09 user manual to facilitate carbon efflux measurements (LI-COR, 2003). Two PVC collars were installed 10 mm into the soil surface in each of the selected plots close the center row of the plot, 1.5 to 3.0 m apart. In plots with camelina present, the PVC collars were installed between camelina rows. At the beginning of each day of measurements, the system was calibrated using the ambient CO<sub>2</sub> level and monitored and adjusted throughout the measurement period.

#### *Soil analysis*

Soil samples were obtained at three points during the growing cycle at three depths (0-15, 15-30, 30-60 cm). In fall 2019, soils were collected within one week of corn harvest at both locations; soil sampling dates spanned 26 September through 16 October across locations. One replicate at the Rosemount site for the 82-day corn hybrid had to be re-sampled with the 90-day corn as the soil samples were left in the field and were not usable for analysis. In spring 2020, soil was sampled at both sites following spring thaw in late April. Soils were sampled only at the Rosemount site following camelina harvest on 15 July. Following soil sampling, soils were dried in a 35°C oven to a constant mass. Soils were then ground and the 0-15 and 15-30 cm samples were combined, so that results could

be compared with prior camelina research on soil nutrient levels (Weyers et al., 2019). Soils were then sent to Agvise Laboratories (Benson, MN) and analyzed for  $\text{NO}_3^-$ , Olsen P, total N, and total C.

#### *Statistical analysis*

The experimental data were analyzed using a linear mixed-effects model in R (version 4.0.4; R Core Team, 2021). Models were constructed using the lmer function of the *lme4* package (version 1.1.27.1; Bates et al., 2015). All data were analyzed with replication and location treated as random effects. However, the fixed effect varied depending on when data for each parameter was collected. Autumn soil samples only had corn relative maturity as a fixed effect while the spring and summer soil samples and camelina ground cover had corn relative maturity, stover presence, and the interaction as fixed effects. Each sampling date with the LI-6400-09 Portable Photosynthesis System was analyzed discretely for differences between treatments. Due to the limited treatments sampled, the fixed effects for this data did not include any interactions and was considered a singular treatment. Following fitting, each model was assessed for analysis of variance (ANOVA) assumptions. Data that did not meet assumptions were  $\log(x)$ -transformed for analysis and back-transformed for presentation. ANOVA ( $\alpha = 0.05$ ) procedures were used to assess fixed effect and interaction significance. When significant differences were found ( $P < 0.05$ ), a mean separation was conducted using Tukey's Honest Significant Differences (HSD) at  $\alpha = 0.05$ .

### **3.4. RESULTS AND DISCUSSION**

#### *Environmental conditions*

Compared with the 30-year normal during the periods of corn, camelina, and soybean growth, the temperature at both experimental sites over the 2019 and 2020 growing seasons was similar to an average year (Table 3-1). Both the Morris and Rosemount sites experienced a warmer-than-typical winter (*i.e.*, December through March) over the period of camelina growth where the average temperature was 1.5 and 1.4°C warmer, respectively, than the 30-year normal temperature over the same months (Table 3-1). Despite the warmer temperatures, camelina growth and development was likely minimally affected as the calculated camelina base temperature is -0.7°C (Allen et al., 2014). Overall, the average temperature at the Morris location over the corn, soybean, and primary camelina (*i.e.*, September through November and April through July) growing seasons was 16.0, 16.5, and 12.1°C and deviated from normal by 0.1, 0.3, and 0.4°C, respectively (Table 3-1). At the Rosemount location, the average temperature over the corn, soybean, and primary camelina growing seasons was 15.9, 16.5, and 12.3°C and deviated from normal by 0.9, 0.3, and 0.2°C, respectively.

Precipitation during the corn growing season was higher than usual while precipitation during the soybean growing season was lower than usual (Table 3-1). Throughout the 2019 growing season, 689 and 778 mm of precipitation fell at the Morris and Rosemount sites, compared with the 30-year normal of 516 and 621 mm, respectively. The elevated levels of precipitation were noticeable at both locations in May, August, and September, and additionally during the month of July in Rosemount (Table 3-1). In contrast, there was a precipitation deficit throughout the 2020 growing season compared with the 30-year normal (Table 3-1). Overall, the Morris site received 141 mm less precipitation than in a normal year, while the Rosemount site received 73 mm less

precipitation. This was especially evident in May and September at both locations, and additionally during the month of July at the Rosemount site, during which 50-60 mm less rain than is typical fell. While precipitation during periods of camelina growth was similar to the 30-year normal, precipitation deviated from normal at multiple points throughout the primary camelina growing season (Table 3-1). Some of this deviation overlapped with that observed during the corn and soybean growing seasons (*i.e.*, September 2019 and May 2020 at both locations). However, precipitation was also notably absent during April 2020 at the Rosemount location when only 8 mm of precipitation were recorded throughout the month, compared with 79 mm in a typical year.

#### *Soil nutrient content*

Over the course of this experiment, there were significant changes in available P,  $\text{NO}_3^-$ , and total N in the topsoil (*i.e.*, 0-30 cm), but only to  $\text{NO}_3^-$  in the subsoil (*i.e.*, 30-60 cm) (Table 3-2). Available P increased in the topsoil between the autumn and spring and remained consistent through the summer sampling interval (Table 3-2). Despite below-freezing temperatures for much of the time between the autumn and spring sampling periods, these results indicate that P became available in the soil profile over that time (Tables 3-1 and 3-2). One source of phosphorus may have been the mineralization of corn stubble, root mass, and the stover that remained in the plots following corn harvest. It has been demonstrated that, even with an average daily temperature of  $-5.7\text{ }^\circ\text{C}$ , there was sufficient decomposition of soil nutrients over the winter months to increase the amount of plant-available phosphorus in the soil profile (Guoju et al., 2012). In addition, daily temperatures were consistently above freezing through the end of November 2019 at both sites, which likely hastened decomposition of corn biomass

following harvest (Table 3-1). An increase in available phosphorus was also observed in one site-year of a prior study that considered the camelina-soybean portion of this corn-camelina-soybean cropping system, but unlike the present experiment, available phosphorus increased in both the topsoil and subsoil (Weyers et al., 2019). The same study found that, while phosphorus had a relative increase between the spring and summer sampling periods, that change was not statistically significant, mirroring the results from the present experiment (Table 3-2; Weyers et al., 2019). While phosphorus is typically applied to camelina during fertilization, there has been little research on the effect of phosphorus on camelina performance (Berti et al., 2016). One prior study suggested that camelina performed best agronomically when phosphorus availability was low (Solis et al., 2013). Within the context of this experiment, the consistency in soil phosphorus between spring and summer may indicate little demand on soil phosphorus reserves and that the phosphorus within the spring fertilizer application was enough to support camelina growth and maturation as well as early season soybean development.

In contrast, total N and  $\text{NO}_3^-$  in the soil profile decreased over the course of this experiment. Total N significantly decreased between the autumn and spring sampling periods while soil  $\text{NO}_3^-$  decreased between the spring and summer sampling periods (Table 3-2). Generally, changes in total N are reflected in the  $\text{NO}_3^-$  levels and it is unclear why that was not the case in the current study (Wall et al., 2013). April, May, and June are often characterized by soil nutrient loss and the decrease in total N between November 2019 and April 2020 may reflect the vulnerabilities during that time period (Table 3-2; Randall and Vetsch, 2005). It is possible that the early season decrease in total N can be attributed to another form of nitrogen (*i.e.*, ammonia or nitrite) in the soil profile rather than  $\text{NO}_3^-$  alone.

Meanwhile, lower-than-average precipitation during early spring 2020 may have diminished the risk of  $\text{NO}_3^-$  loss (Tables 3-1 and 3-2; Randall and Vetsch, 2005; Weyers et al., 2021). These findings were consistent with prior research that focused on the camelina-soybean portion of the cropping rotation and did not observe soil  $\text{NO}_3^-$  loss between the autumn and spring (Weyers et al., 2019). Despite spring fertilization, soil  $\text{NO}_3^-$  declined by 13 and 9  $\text{kg ha}^{-1}$  in the top- and subsoil, respectively, between the spring and summer sampling intervals (Table 3-2). This was likely due to nutrient utilization from both the camelina and soybean as well as heavy rainfall events in late June and early July (Table 3-1). At the time of summer sampling in the present experiment, camelina had completed its lifecycle and soybean had transitioned from the vegetative phase to the reproductive phase (data not shown). By R2, soybean typically utilizes about 65  $\text{kg ha}^{-1}$  of N and it was reported that camelina utilizes between 85 and 112  $\text{kg ha}^{-1}$  of N over its life cycle when fertilized at a similar rate to the present study (Bender et al., 2015; Malhi et al., 2014). This, in conjunction with the decline in soil  $\text{NO}_3^-$ , may indicate that the  $\text{NO}_3^-$  in the soil profile and spring-applied fertilizer was quickly utilized by both the camelina and soybean in the late spring and early summer months. It is also worth noting that there was consistent weed pressure throughout late June and early July at the Rosemount site (personal observation). This may have contributed to increased nitrogen uptake from the soil profile and is reflected in the summer sampling values as only data from the Rosemount site was collected during that sampling interval (Table 3-2). These results were contrary to the results reported by Weyers et al. (2019) who observed that soil  $\text{NO}_3^-$  increased between spring and summer sampling, likely an indication that winter oilseed biomass mineralization occurred between sampling intervals. While biomass mineralization was not

evident within the bounds of the present study, it is possible that the camelina biomass would have broken down enough for an appreciable difference in soil  $\text{NO}_3^-$  by the time of soybean harvest.

In addition to global changes across sampling intervals, soil  $\text{NO}_3^-$  had treatment-level differences within the spring and summer sampling periods at both the 0-30 and 30-60 cm depths (Table 3-2). Treatment effect varied by sampling depth where corn relative maturity had a significant effect on  $\text{NO}_3^-$  from 0-30 cm while stover presence had a significant effect on  $\text{NO}_3^-$  from 30-60 cm (Table 3-3). Overall, corn relative maturity treatments with camelina present retained more  $\text{NO}_3^-$  in the soil profile compared with the fallow control at the spring sampling date (Table 3-3). Based on prior findings, it was expected that the treatments that included camelina would provide winter cover and thus mitigate early spring nutrient loss when compared with the fallow treatment (Johnson et al., 2017). However, the 82 RM treatment (*i.e.*, the earliest camelina planting date) performed similarly to the control, which may have been due to the contrasting amounts of living cover within those respective treatments (Tables 3-3 and 3-4). The control had no living cover at the time of spring sampling, meaning that these plots were more susceptible to nutrient loss between the autumn and spring sampling intervals (Johnson et al., 2017; Randall and Vetsch, 2005). On the other hand, the 82 RM plots had the most living cover present in both the autumn and spring, which may have begun to utilize available nutrients more rapidly than the other camelina treatments (Table 3-4). While there are currently no nitrogen utilization studies specific to camelina, a study on spring canola found that of vegetative parts, leaves had the highest levels of nitrogen (Svečnjak and Rengel, 2006). Based on this, early season camelina biomass was likely nitrogen-rich and may have led to

the relative decrease in  $\text{NO}_3^-$  in the soil profile under the 82 RM treatment (Table 3-3). It is unclear why the 90 and 95 RM treatments retained more  $\text{NO}_3^-$  than the control treatment as they had significantly less ground cover than the 82 RM treatment in both the autumn and spring. However, it is possible that the lower-than-average amount of early spring precipitation combined with the lack of living cover to uptake nutrients allowed for the  $\text{NO}_3^-$  to remain undisturbed in the soil profile between the autumn and spring sampling periods (Tables 3-1, 3-3, and 3-4).

By camelina harvest (*i.e.*, the summer sampling interval), only the control and 95 RM treatments performed differently from each other (Table 3-3). It should be noted that only plots with camelina were fertilized in spring 2020 to reflect current best management practices for both soybean and camelina. Due to this, it was expected that the control plots would have an overall lower amount of  $\text{NO}_3^-$  within the soil profile than the relay-cropped treatments (Weyers et al., 2021). In addition, early summer weed pressure may have had a more noticeable effect on  $\text{NO}_3^-$  levels in the soybean-only plots despite similar soybean yields across the 95 RM and control treatments (Fig. 2-5). One prior study found that 76 cm soybean row spacing corresponded with a greater amount of early season weed pressure when compared with soybeans planted with narrower row spacing (Knezevic et al., 2003). The soybean in the present study were spaced 76 cm apart, which resulted in a canopy that never fully spanned the space between soybean rows and may have left the control treatments particularly susceptible to weed pressure even after canopy closure (personal observation). Despite low camelina yields in the 95 RM plots compared with the other camelina treatments, the 95 RM camelina was likely able to provide essential weed

suppression between the soybean rows while requiring relatively less  $\text{NO}_3^-$  than the 82 and 90 RM treatments (Fig. 2-2; Royo-Esnal and Valencia-Gredilla, 2018).

There were also changes to subsoil  $\text{NO}_3^-$  during the spring and summer sampling intervals (Table 3-3). At the time of sampling in the spring,  $\text{NO}_3^-$  under plots without stover was greater than in plots with corn stover (Table 3-3). These findings were corroborated by a recently published study, which found that fields where corn stover was removed had higher levels of  $\text{NO}_3^-$  in the soil profile compared with fields where stover was incorporated (Galindo et al., 2022). However, these findings may not be applicable as Galindo et al. (2022) only examined the top 20 cm of the soil profile compared with the 30-60 cm depth in the present study (Table 3-3). It is also unclear whether mineralized corn biomass would infiltrate the soil profile to 30-60 cm while showing no treatment-wide differences at 0-30 cm. At the time of camelina harvest, the plots with stover had a greater amount of  $\text{NO}_3^-$  than the stover removal plots (Table 3-3). Camelina yields were significantly higher in plots where stover was removed, which may have led to a greater amount of nutrient removal from the soil profile compared with the plots where stover remained (Fig. 2-3). The camelina root system is relatively shallow and the majority of the root density is present within the top 30 cm of the soil (Gesch and Johnson, 2015). Despite this, there may have been enough nutrient scavenging within the subsoil to decrease the amount of  $\text{NO}_3^-$  in soil profile especially in the no stover plots where camelina yields were higher (Fig. 2-3). In addition, there is evidence that stover removal corresponds with a decrease in soil available nutrients, which may partially explain the overall decrease in  $\text{NO}_3^-$  in plots where corn stover was removed (Table 3-3; Galindo et al., 2022). The results of this study span only two sites over two growing seasons and the implications of stover removal may not

be truly understood until after the corn-camelina-soybean cropping rotation is in effect for multiple seasons. Research indicates that continuous stover removal has a negative impact on soil fertility, but prior studies have mainly focused on the effects within the topsoil (Blanco-Canqui and Lal, 2009; Galindo et al., 2022). Continued research on nutrient retention and loss under this cropping system over time will be essential to ensuring that it can be sustainably integrated onto the landscape.

#### *Soil carbon dioxide flux*

Soil CO<sub>2</sub> flux was measured over the spring portion of the primary camelina growing season, spanning mid-April through mid-July (Fig. 3-1). Overall, soil CO<sub>2</sub> efflux was consistently higher in the fallow control plots relative to the plots that contained camelina. However, there were significant differences between the two treatments at only a few points in time. These differences occurred principally in the spring just before and after soybean planting, potentially due to the relative variation in vegetation between the treatments (Fig. 3-1). The control treatment with stover present generally represented a middle ground between the other two treatments, performing similarly to one or both of the other treatments for all measurements but the 10 June sampling date. It is unclear why the Control x Stover treatment differed on 10 June. An increase in soil temperature corresponds with an increase in soil efflux (Ray et al., 2020). The soil temperature was somewhat cooler than in the two previous weeks, however, it is unlikely that this had an appreciable effect on just one treatment given the similarities in treatment performance on other sampling dates (data not shown; Fig. 3-1). The differences between treatments may merely be an indicator of in-field variation. It is also interesting to note the sharp increase in CO<sub>2</sub> flux between the 19 June and 1 July sampling dates (Fig. 3-1). This was likely a

function of the increase in precipitation over that period (Table 3-1). Soil CO<sub>2</sub> emissions are strongly tied to precipitation events, one study found that 91% of the variance in soil CO<sub>2</sub> efflux in the four to 72 h after rainfall could be tied to that precipitation event (Reth et al., 2005; Tan et al., 2021). Within 72 h prior to the 25 June sampling, 49 cm of rain fell, while 110 cm of rain fell prior to the 1 July sampling date (Table 3-1). These precipitation events likely left the soil saturated and evacuated CO<sub>2</sub> from the soil pores, increasing the measured CO<sub>2</sub> efflux (Fig. 3-1; Deng et al., 2017). Despite a significant amount of living cover in all the treatments by the 25 June sampling date, the 82 RM x No stover treatment did not experience a similar rate of CO<sub>2</sub> emissions compared with the other treatments (Fig. 3-1). The placement of the PVC collars was equidistant between soybean rows, meaning that the control plots did not have living cover in the immediate vicinity of the collars, while the 82 RM x No stover treatment had camelina directly on either side of the PVC collars. Camelina has a shallow root zone, but may have been able to increase the amount of infiltration through the soil profile compared with the soybean-only plots (Gesch and Johnson, 2015; Sustainable Agriculture Research & Education program, 2012). However, it is possible that this is another example of in-field sampling variation.

To date, no published studies have focused on the effect of camelina on greenhouse gas emissions. However, studies conducted in the greater Midwest region have found little evidence to support the idea that cover crops effectively reduce CO<sub>2</sub> emissions compared with no cover treatments (Behnke and Villamil, 2019; Negassa et al., 2015). In another study that considered variations of the corn-soybean rotation, it was determined that the relatively diversified corn-soybean-wheat system had a similar daily soil CO<sub>2</sub> emission rate when compared with both a corn-soybean and soybean-corn rotation (Behnke et al., 2018).

This was similar to the present study as the camelina treatment had a CO<sub>2</sub> flux rate similar to one or both of the controls on all sampling dates except 1 July (Fig. 3-1). A recent meta-analysis focusing on cover crops spanning global production environments found that the presence of a cover crop led to an increase in CO<sub>2</sub> emissions, likely due to the addition of carbon-rich biomass and increased microbial activity in the soil profile (Muhammad et al., 2019). While these overall findings contradict the results from the present study as well as other studies in the Midwest region, Muhammad et al. (2019) also concluded that, while CO<sub>2</sub> efflux from treatments with cover crops was still greater than treatments without, there was relatively little difference in CO<sub>2</sub> emissions between the two cropping scenarios on silty loam soils. These findings more closely align with the results from the present study as the Rosemount site, where the CO<sub>2</sub> flux data was collected, features a silt loam soil and the treatments performed similarly overall (Fig. 3-1). Based on the limited data collected in this study as well as the variation in results from prior research, it is difficult to draw conclusions about the specific effect of camelina on CO<sub>2</sub> flux. It is evident that further research is needed to better understand the effect of camelina presence on greenhouse gas emissions within the corn-camelina-soybean cropping rotation.

The effect of stover removal on CO<sub>2</sub> flux has been well documented in the Upper Midwest. A recent review that focused on the impacts of corn stover removal on greenhouse gas emissions indicated that treatments where corn stover was removed experienced reduced CO<sub>2</sub> loss compared with treatments where stover remained on the soil surface (Battaglia et al., 2021). Higher CO<sub>2</sub> emissions where stover was not removed was likely a result of the vegetation available for microbial incorporation, similar to the effect of cover crops versus fallow land (Battaglia et al., 2021; Muhammad et al., 2019). The

results from this study contradict the previous conclusions. There was no clear relationship between stover removal and CO<sub>2</sub> flux as the treatments with and without stover performed similarly to each other at all but one of the sampling intervals (Fig. 3-1). This may have been due to the fact that sampling took place over a very small portion of the camelina growing season (*i.e.*, over a few hours once per week). Because of this, the data is naturally sparse and likely does not provide a wholistic representation of the CO<sub>2</sub> flux over the growing season. However, short-term experimental data from other studies did find similar results compared with this experiment. Baker et al. (2014), which looked at zero, full, and intermediate stover removal, did not observe any statistical differences in CO<sub>2</sub> emissions between treatments over the first year of the study. Over the 3-year duration, however, there were cumulative differences in soil CO<sub>2</sub> efflux. This likely indicates that a long-term study of continuous stover presence versus absence is needed to determine the true global differences between corn-soybean best management practice treatments and those that include camelina. Other studies that focused on a stover removal gradient rather than full and no removal found no statistical differences between stover removal scenarios despite researchers observing a correlation between stover removal and simulated CO<sub>2</sub> emissions (Drury et al., 2021; O'Brien et al., 2020). It is also interesting to note that, despite lower rates of CO<sub>2</sub> efflux when stover was removed, it was implied that there was overall greater soil organic carbon loss from the systems where stover was removed due to reduced carbon input via stover (O'Brien et al., 2020). A decrease in total C was not observed within this study, but again, continual stover removal may yield similar to results to prior experiments (Table 3-2).

While the soil respiration values measured in this study provide a baseline for a corn-camelina-soybean rotation versus the management practices within a typical grain or silage corn operation (*i.e.*, the Control x Stover and Control x No stover treatments, respectively), they provide a static picture of the soil CO<sub>2</sub> flux over time that, overall, did not align with the results from prior long-term research. It is clear that future research needs to include long-term efforts to capture a full picture of the CO<sub>2</sub> emissions from the corn-camelina-soybean rotation. In addition, including treatments over a fully crossed design may make it easier to determine what effects are individually associated with camelina and stover presence/absence. While not specifically addressed in this research, other greenhouse gases that are typically measured (*i.e.*, methane and nitrous oxide) in cropping systems research should be characterized within the corn-camelina-soybean system as well (Baker et al., 2014; Behnke et al., 2018; Drury et al., 2021). It would also be prudent to include deployable chambers with automatic sampling in future studies to better gather information over the entirety of the camelina growing season rather than through weekly snapshots.

#### *Soil carbon*

The carbon cycle is not limited to soil CO<sub>2</sub> flux and includes an interconnected cycle between vegetation, soil, and atmosphere. Over the course of this study, the amount of total carbon did not change within the soil profile or across treatments (Table 3-2). There was a relative decrease in soil C between the spring and summer sampling periods, which was likely because both the Rosemount and Morris sites were sampled in the spring, but only the Rosemount site was sampled in the summer. Despite the obvious losses from soil CO<sub>2</sub> emissions, the total carbon values may indicate that there was little loss from the

system over the time period of this experiment (Fig. 3-1; Table 3-2). However, a decrease in soil organic matter and soil organic carbon has been reported in numerous studies as a result of corn stover removal (Battaglia et al., 2021). This discrepancy is likely because the scope of the current experiment was relatively small, time-wise, and changes in soil properties often do not occur until a cropping practice has been implemented for multiple consecutive growing seasons. Prior research has generally spanned three or more full consecutive growing seasons as opposed to a single growing season following stover removal as in the present study (Battaglia et al., 2021). With a greater number of years and sampling intervals, changes to soil organic carbon may become more evident. Cover crops have been shown to reduce the impact of stover removal in both continuous corn and corn-soybean systems, thus one of the principal environmental questions of interest is whether camelina biomass can offset the carbon loss due to stover removal (Blanco-Canqui et al., 2014; Osborne et al., 2014; Sindelar et al., 2017). However, this question cannot be answered with the data collected over the course of this experiment. Recent research suggests that winter oilseed biomass mineralization occurs relatively quickly, which can lead to changes in soil health and nutrients within the soil profile (Weyers et al., 2019). At the very least, soil sampling should continue through the fall to soybean harvest, so that camelina biomass has the chance to breakdown and integrate into the soil profile and the effects of both stover removal and camelina biomass on soil carbon can be better understood.

### **3.5. CONCLUSIONS**

It is difficult to draw conclusions based on two site-years of data as the parameters assessed in this experiment typically change slowly over long periods of time rather than within a single growing season. Based on prior research and these preliminary results, a well-established stand of camelina may be able to mitigate early season nutrient loss. The soil nutrient results in this study were largely consistent with what has been found in prior research, but sampling through soybean harvest may provide a wholistic picture of the nutrient cycling within the corn-camelina-soybean rotation as other studies have not included the corn portion of the cropping rotation. In addition, further research is needed to better understand the role of camelina in the carbon cycle. These results show little change in CO<sub>2</sub> flux and soil carbon over the one year where stover was removed and camelina was planted. Prior research has indicated that the changes resulting from cover crop integration and stover removal occur over years rather than months. A full lifecycle analysis focusing on changes in carbon over multiple years will help to clarify these results. Further research should also consider measuring additional greenhouse gases (*i.e.*, methane and nitrous oxide) using field-deployable automated sampling changes to gather a more refined picture of soil emissions. The difficulty of measuring global change in soil nutrients and soil health properties lies in time and spatial variance. It will be necessary to conduct long-term research to truly understand how integrating camelina into the corn-soybean rotation can change the sustainability of the agricultural landscape.

### **3.6. TABLES AND FIGURES**

Table 3-1. Mean monthly air temperature and cumulative precipitation over the 2019 and 2020 growing season at the Morris and Rosemount, MN experimental sites.

| Crop     | Year | Month | Morris, MN  |                    |               |                    | Rosemount, MN |                    |               |                    |
|----------|------|-------|-------------|--------------------|---------------|--------------------|---------------|--------------------|---------------|--------------------|
|          |      |       | Temperature |                    | Precipitation |                    | Temperature   |                    | Precipitation |                    |
|          |      |       | Mean<br>°C  | 30-year<br>average | Total<br>mm   | 30-year<br>average | Mean<br>°C    | 30-year<br>average | Total<br>mm   | 30-year<br>average |
| Corn     | 2019 | May   | 11.8        | 13.5               | 105.9         | 78.7               | 11.6          | 14.0               | 173.0         | 109.7              |
|          |      | June  | 19.8        | 19.3               | 79.0          | 111.3              | 19.9          | 19.6               | 76.2          | 124.0              |
|          |      | July  | 22.2        | 21.3               | 111.0         | 108.0              | 22.0          | 21.7               | 179.6         | 114.6              |
|          |      | Aug   | 19.5        | 19.9               | 136.7         | 87.9               | 17.5          | 20.4               | 94.0          | 112.5              |
|          |      | Sept  | 17.1        | 15.5               | 177.5         | 68.1               | 17.6          | 16.2               | 146.1         | 87.4               |
|          |      | Oct   | 5.9         | 7.5                | 79.3          | 62.0               | 6.8           | 8.7                | 109.0         | 72.6               |
|          |      | Nov   | -2.0        | -1.1               | 9.1           | 25.1               | -2.1          | 0.3                | 27.4          | 43.4               |
| Camelina | 2020 | Dec   | -8.2        | -8.6               | 27.4          | 19.1               | -6.6          | -7.1               | 35.3          | 30.7               |
|          |      | Jan   | -9.9        | -12.3              | 13.7          | 18.3               | -7.7          | -10.7              | 58.4          | 24.4               |
|          |      | Feb   | -9.5        | -10.1              | 2.8           | 18.8               | -8.5          | -8.3               | 15.2          | 22.9               |
|          |      | Mar   | 0.1         | -2.6               | 9.7           | 30.5               | 1.1           | -1.0               | 34.5          | 45.7               |
|          |      | Apr   | 5.2         | 5.8                | 38.1          | 56.9               | 6.1           | 7.1                | 0.0           | 78.7               |
|          |      | May   | 13.3        | 13.5               | 26.7          | 78.7               | 13.6          | 14.0               | 57.2          | 109.7              |
|          |      | June  | 22.0        | 19.3               | 111.8         | 111.3              | 21.1          | 19.6               | 227.8         | 124.0              |
| Soybean  |      | July  | 22.8        | 21.3               | 115.8         | 108.0              | 23.1          | 21.7               | 57.7          | 114.6              |
|          |      | Aug   | 21.3        | 19.9               | 71.1          | 87.9               | 21.3          | 20.4               | 101.1         | 112.5              |
|          |      | Sept  | 15.0        | 15.5               | 17.5          | 68.1               | 14.8          | 16.2               | 27.9          | 87.4               |
|          |      | Oct   | 4.5         | 7.5                | 32.3          | 62.0               | 4.9           | 8.7                | 76.5          | 72.6               |

Table 3-2. Average soil nutrient values taken at depths of 0-30 and 30-60 cm in autumn 2019, spring 2020, and summer 2020.

| Sampling interval | 0-30 cm                      |       |                    |         | 30-60 cm                     |     |                    |         |
|-------------------|------------------------------|-------|--------------------|---------|------------------------------|-----|--------------------|---------|
|                   | NO <sub>3</sub> <sup>-</sup> | P     | Total N            | Total C | NO <sub>3</sub> <sup>-</sup> | P   | Total N            | Total C |
|                   | kg ha <sup>-1</sup>          | ppm   | g kg <sup>-1</sup> |         | kg ha <sup>-1</sup>          | ppm | g kg <sup>-1</sup> |         |
| Autumn 2019       | 25a†                         | 7.3b  | 0.15a              | 1.68    | 25a                          | 5.0 | 0.10               | 1.87    |
| Spring 2020       | 22a‡                         | 9.6ab | 0.14b              | 1.68    | 18a‡                         | 5.5 | 0.09               | 1.89    |
| Summer 2020 ¶     | 9b‡                          | 11.9a | 0.13b              | 1.48    | 9b‡                          | 8.4 | 0.12               | 1.53    |

† Letters within a column indicate a significant difference based on Tukey's HSD ( $P < 0.05$ ) over sampling intervals within a depth and nutrient.

‡ NO<sub>3</sub><sup>-</sup> measurements within a depth and sampling interval were statistically significant based on Tukey's HSD ( $P < 0.05$ ), see Table 3 for detailed mean separation.

¶ Summer 2020 sampling occurred only at the Rosemount, MN site.

Table 3-3. Significant soil NO<sub>3</sub><sup>-</sup> within a depth, sampling interval, and treatment.

| Sampling interval | 0-30 cm             |       |       |       | 30-60 cm            |           |
|-------------------|---------------------|-------|-------|-------|---------------------|-----------|
|                   | Control             | 82 RM | 90 RM | 95 RM | Stover              | No stover |
|                   | kg ha <sup>-1</sup> |       |       |       | kg ha <sup>-1</sup> |           |
| Spring 2020       | 17b‡                | 20ab  | 25a   | 24a   | 16b                 | 19a       |
| Summer 2020       | 6b                  | 9ab   | 10ab  | 12a   | 10a                 | 8b        |

† Lowercase letters within a depth and sampling interval indicate a significant difference in NO<sub>3</sub><sup>-</sup> between treatments based on Tukey's HSD ( $P < 0.05$ ).

‡ statistically significant, see Table X for mean separation.

‡ NO<sub>3</sub><sup>-</sup> measurements between 30-60 cm were statistically significant, see Table Y for mean separation.

Table 3-4. Camelina seed and stem and leaf biomass quality by main effect and interaction. Values within an effect and column that share a letter are not statistically significant from each other based on Tukey's HSD ( $P < 0.05$ ). Values within an effect and column that do not have letters were not significant from each other.

| Treatment           | Ground cover |        |
|---------------------|--------------|--------|
|                     | Fall         | Spring |
|                     | %            |        |
| Control             | ---          | ---    |
| 82 RM               | 0.44a        | 4.84a  |
| 90 RM               | 0.14b        | 0.65b  |
| 95 RM               | 0.01c        | 0.16b  |
| Stover              | 0.08b        | 0.69b  |
| No stover           | 0.28a        | 2.55a  |
| Control x Stover    | ---          | ---    |
| Control x No stover | ---          | ---    |
| 82 RM x Stover      | 0.18bc       | 2.09b  |
| 82 RM x No stover   | 0.79a        | 6.56a  |
| 90 RM x Stover      | 0.06cd       | 0.39cd |
| 90 RM x No stover   | 0.22b        | 0.87bc |
| 95 RM x Stover      | 0.01d        | 0.08d  |
| 95 RM x No stover   | 0.01d        | 0.24cd |

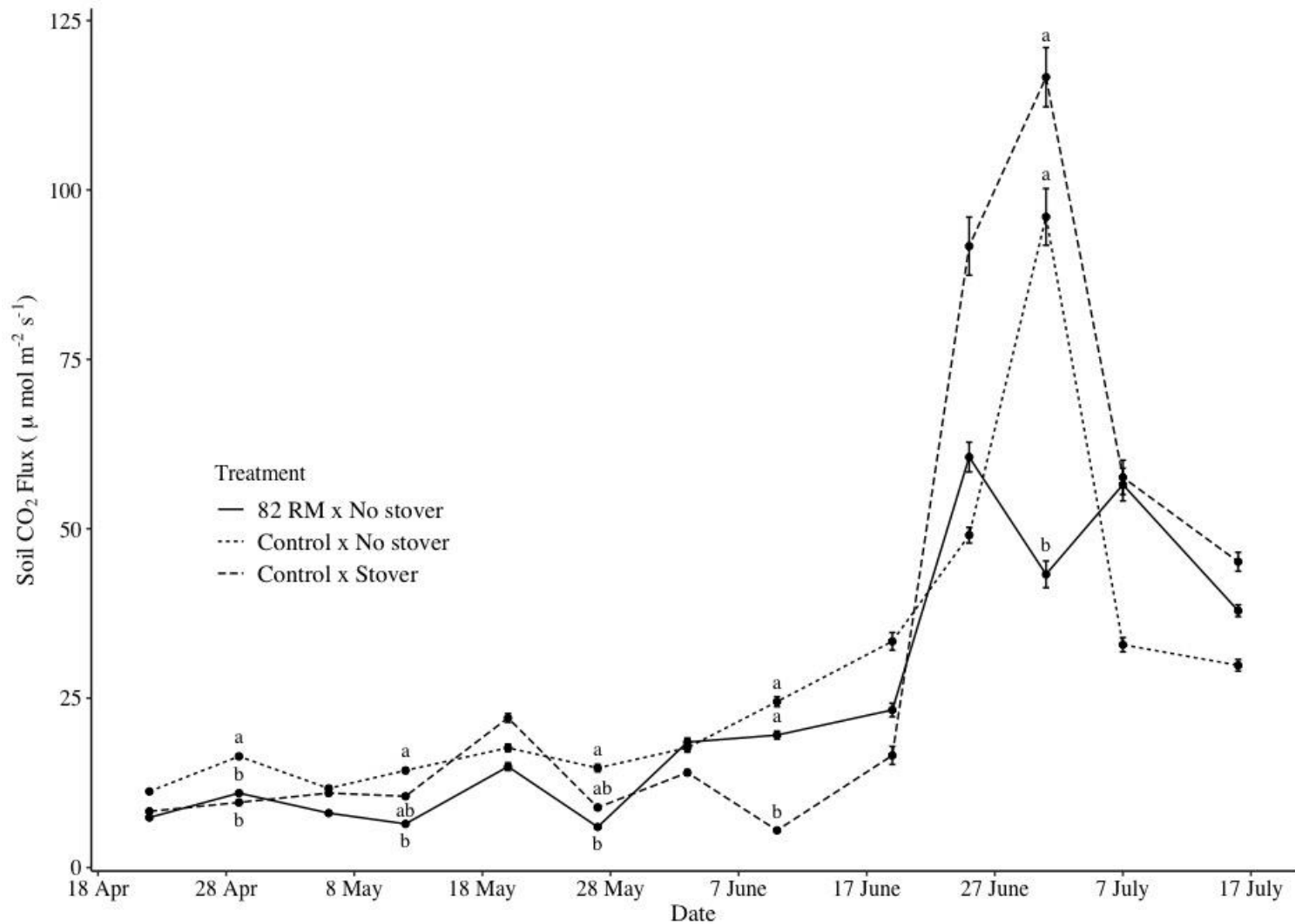


Figure 3-1. The effect of corn relative maturity treatment by stover presence on soil CO<sub>2</sub> flux by date. Within a date, treatments that share a letter are not statistically significant from each other based on Tukey's HSD ( $P < 0.05$ ). Values are means  $\pm$  S.E.,  $n = 6$ .

## **4. CAN WE GET HOOKED ON SCIENCE? THE OPPORTUNITIES AND CHALLENGES OF CREATING A SCIENCE PODCAST IN AN ACADEMIC SETTING**

### **4.1. SUMMARY**

Historically, the dissemination and contextualization of scientific ideas to general audiences has been the responsibility of non-partisan science journalists. However, there is an increasing demand for academic researchers to directly communicate their work with the public. Despite need, there is little formal training in academia focused on conveying scientific information in informal settings. This has resulted in a do-it-yourself approach to disseminating complex scientific information to general audiences. One method that has been attractive to young researchers has been podcasts. Podcasts can be a conversational and learner-friendly tool to share scientific information. Thus, the goal of this experiential project was to host and produce a science podcast with an emphasis on opportunities for early-career researchers to share their science. A podcast, *Hooked on Science*, was developed and launched in February 2020 to meet this goal. Episodes were targeted to general audiences and featured a variety of scientific topics spanning seven distinct disciplines. There were many benefits to podcast production including networking with other scientists and content creators, developing new skillsets, and improving scientific communication skills. Podcast production also had its challenges such as intense time demands, guest management, and managing expectations. In order to make alternative science communication methods more accessible in the future, graduate programs should consider providing better education to students around communicating research in informal settings as well as emphasize the importance of practicing science communication outside of conference presentations and manuscript development.

## 4.2. INTRODUCTION

Academic research is typically disseminated through two main avenues: journal articles and conferences. These channels exist to communicate complex and critical ideas between scientific peers, but the information shared through these avenues is typically inaccessible and difficult to comprehend by general audiences (Falkowski and Sparks, 2020; Figueroa, 2022; Plavén-Sigra et al., 2017). For decades, the communication of novel scientific information fell in the hands of non-partisan science journalists who were able to translate complex ideas into digestible media for the public, but dedicated scientific journalists are becoming an increasingly rare commodity (Dunwoody et al., 2009; Nisbet and Scheufele, 2009; Scheufele, 2013). Thus, there is a rising expectation that scientists directly, but informally, communicate their research to the general public. The current structure of academia can make this difficult. Few types of science communication are validated in academic settings, meaning that many researchers lack incentive to share their work outside of what is deemed acceptable for promotions (*i.e.*, tenure or rank advancement) (Scheufele, 2013). In addition, many scientists do not have experience communicating their research to audiences outside of their academic peers due to a systemic lack of emphasis on developing effective informal science communication skills (Brownell et al., 2013; Kuehne et al., 2014). This is well-known weakness in higher education, particularly at the graduate level, which has resulted in a do-it-yourself (DIY) approach to science communication (Kuehne et al., 2014). There are a wide range of benefits that can stem from a DIY approach, such as tailoring the communication method to an individual's current skills, time investment, or their certainty of reaching target

audiences. One approach that has attracted scientists and educators, particularly young researchers, is podcasting (MacKenzie, 2019; Picardi and Regina, 2008).

Podcasts were initially developed in 2004 by Mark Curry as a way to automatically download MP3 files and have exploded in popularity in the nearly two decades since (McClung and Johnson, 2010). Podcasting can be a relatively straightforward way to disseminate content as episodes can easily be produced using technology that most people use daily (*i.e.*, a cell phone or computer) and can be uploaded and distributed worldwide through free hosting sites. While podcasts have been used in higher education as a course revision tool or a primary education tool for students, there are opportunities to use podcasting as a medium through which scientists can share their research as well (Davidson et al., 2019; Luna and Cullen, 2011; MacKenzie, 2019; Malecki et al., 2019; Taylor, 2009). In a recent media-usage survey, 38% of the US population over 12 listened to podcasts monthly, more than double the number of people listening in 2015 (Edison Research, 2022). The average person listens to eight podcasts per week indicating that there are ample opportunities for research to reach new and existing audiences via podcast. Due to their length, science-driven podcasts can contain all the typical parts of an academic research paper (*i.e.*, introduction, materials and methods, results, and discussion) while integrating a more casual tone and a relaxed dialogue (Drew, 2017; Ye, 2021). The informality of a podcast can help listeners feel as though they are talking with friends rather than being lectured on content, further highlighting the importance education surrounding informal science communication (Robson, 2021). Including academic researchers on podcasts can benefit both the scientist as well as the podcast itself. Speaker credentials, hosts and guests associated with academic institution, can help podcasts gain credibility as an educational

medium as the information from trustworthy primary sources is typically perceived as accurate and reliable (Lim and Swenson, 2021; Riddell et al., 2020). To date, many science podcasts have been conceived as a way to reach general audiences, however, outside of production data, there is little transparency about the process of creating a podcast in an academic setting (MacKenzie, 2019). Thus, the objective of this experiential project was to host and produce a science podcast as a method to communicate science with the public while emphasizing opportunities for early-career researchers to improve their informal science communication skills.

### **4.3. HOOKED ON SCIENCE: A CASE STUDY IN PODCASTING**

#### *Show format*

Hooked on Science was conceived as an interview-based science podcast where early career scientists could practice their science communication skills, gain exposure to podcasting as a research dissemination method, and make their science available to a general audience in an accessible format. While early career scientists were the main group targeted for interviews, guests varied in their careers and years of experience though all were associated with an academic institution (Fig. 4-1). Episodes were intended for bi-weekly release, but averaged 1.5 episodes per month during active periods of the show (Table 4-1). Each show began with a guest introduction and some essential background information to contextualize the episode's topic while the second half focused on the methods and results from a research project of the guest's choosing. The idea behind this episode structure was that listeners of all knowledge levels could engage with the material regardless of their background and could decide whether they wanted to learn generally or

more in depth about an episode's topic (*i.e.*, listen only to the first half of the episode or listen to an episode in its entirety). Occasionally episodes varied from the typical structure when a research conversation focused on more than two topics, each for a significant amount of time, and the recording was split into a main episode and a bonus episode (Table 4-1). Each episode featured a call to action for listeners to join the online Twitter, Facebook, or Instagram communities and early episodes ended with interesting facts sent in by a listener.

### *Benefits and opportunities*

While podcasting had many challenges, the benefits largely outweighed the negative aspects. Hooked on Science was born and officially launched in February 2020. This timing was critical as I was able to, unknowingly, establish Hooked on Science prior to the shutdowns that are now synonymous with the COVID-19 pandemic. Graduate school often goes hand in hand with networking, typically in a conference setting, however, that was no longer possible due to pandemic restrictions. At best, online conferences were clunky and disorganized and did not allow for natural conversations to take place in the same way that they had during in-person events. Thus, it was difficult to maintain the same level of professional networking through the usual methods and working on a podcast offered a way to connect with people during a period of distinct isolation. Developing new relationships was not limited to the guests that I had on my podcast, but also stretched to the greater podcasting community. I found that the network of science podcasters I connected with were friendly, inviting, and interested in connecting on both a personal and professional level. Within the community, I was able to develop relationships with other academic podcasters, which gave me the opportunity to interview them about their

research as well as practice my own science communication skills as a guest on their respective shows (Baliga, 2021; Haraden and McCormick, 2021; Schafer, 2021). Participating as a podcast guest gave me better insight into how to become a better host and podcast administrator as well as practice delivering my research content through a medium that was new to me as a scientist. Podcast production required me to consistently read transcripts and review audio for my episodes. This process gave me a lot of insight into the science communication process and helped me to be more cognizant of common shortcomings as well as some effective strategies to use when talking about research while recording a podcast.

Outside of developing new relationships and practicing science communication skills, podcasting required me to develop a variety of new technical and soft skills. As a one-woman show, I had to wear many proverbial hats to keep *Hooked on Science* running smoothly; I was the show's administrator, host, editor, producer, graphic designer, and social media manager. Juggling these roles was, at times, overwhelming, but my Extension background in presenting scientific research to general audiences helped to ease the burden. While not everyone in an academic setting has the opportunity to regularly present their research to non-technical audiences, understanding the process of translating information from scientific jargon to accessible language was an integral part of podcast production. From this standpoint, interviewing guests within the plant sciences resulted in some of the most difficult-to-edit interviews as it was easy to fall into discipline-specific language and it could be difficult to remember what constituted domain knowledge versus general knowledge. On the other hand, episodes where I interviewed guests outside of the plant sciences often resulted in more conversational episodes because my lack of prior

knowledge meant that I was genuinely surprised or curious about the answers that guests gave me. In short, I was able to directly play the role of a general audience member when interviewing guests in fields outside my academic domain. Regardless of the episode topic, interviewing guests was something I had never done before and required a delicate balance of interjection and active listening. This was a skill that I developed over time, but was integral to the success of each episode as the interviews resulted in the show's core content. In my experience, the conversational style required for podcasting differed from one-on-one research conversations that I've had in other settings. The information shared via podcast had to be more concise and allow for discussion rather than the long explanations that can often occur when talking about topic that someone has expertise in. The conversational style synonymous with podcasts is contrary to the way that research is often presented in academia and many guests did not have practical experience communicating using this technique. Because of this, I was able to hone my editing and production skills by breaking up conversational tangents and monologues to make the information more engaging and digestible for listeners.

Hooked on Science also required me to engage in a new creative process by developing brand materials. In order to create a brand kit, I had to become more familiar with graphic design and understand the graphics I needed to distribute Hooked on Science and successfully promote the show on various social media sites throughout the episode post-production process. To meet these needs, I created a brand kit that included a logo, an infographic for potential guests, and graphics for episodes to advertise their release that were formatted for Facebook, Instagram, and Twitter (Fig. 4-2). While it was initially time consuming to develop these materials, the brand kit was an essential part of Hooked on

Science's presence on social media as it allowed for brand recognition, continuity between posts, and streamlined the posting process. My social media presence also helped the show to grow a reputation online as a legitimate science communication podcast that allowed me to connect with guests and listeners across the globe. Between social media, guest connections, and the global nature of podcast distribution, I was able to garner a global audience, greatly expanding the reach of Hooked on Science outside my primary and secondary contacts. Hooked on Science listeners spanned 39 U.S. states and 49 countries worldwide, many of whom I would not have reached without the ability to connect and share via social media sites (Fig. 4-3). Overall, creating and maintaining Hooked on Science allowed me to develop novel skills, new professional and personal relationships, and create an enduring record of scientific topics available for people worldwide.

### *Challenges*

While podcasting had many rewarding aspects, creating and maintaining an educational podcast was not without its difficulties. The major challenges I faced when working on Hooked on Science included the time to produce a professional product, guest management, and managing my expectations. While many online resources touted the ease of access to podcast creation tools (*i.e.*, using headphones for a microphone, a cell phone as the recording device, and free hosting platforms), few talked about the time required to maintain an active educational podcast. I found that each episode took about ten hours to produce, which accounted for interview preparation, the interview itself, and episode editing. As Hooked on Science was a self-directed project, I produced 1-3 episodes per month based on my academic schedule and guest availability, which allowed me to choose the weeks where I could accommodate the time required to produce an episode (Table 4-

1). While I benefitted from the lack of structure, it was difficult to maintain an audience without consistent episode releases. Much of my podcast listenership was acquired through guest's personal and professional networks. In the weeks that did not have episodes, it was difficult to reach new listeners and plays often plateaued. It is also important to acknowledge that there was a demanding behind-the-scenes administrative workload even in weeks when no episodes were published. One piece of this was engaging with listeners on social media. It was much easier to produce content when there was a recent episode release, whereas it was much more difficult to produce social media content during the weeks or months without episodes. As a result, my time devoted to social media in any given week could be quickly doubled or tripled. While social media was not an essential piece to making the podcast itself, it felt like a critical piece to maintain my audience and connect with the indie podcasting community. Recognizing the time demands of podcasting is an integral step to understanding the process and something that any future podcasters, especially those with other academic demands, should keep in mind.

Aside from time demands, the most difficult, but essential, part of producing *Hooked on Science* was identifying, connecting with, and scheduling interviews with guests. While the interviews themselves were fun and engaging, it could be a long and arduous process to reach the interview itself. I typically found my guests through social media and referrals, but "cold calling" potential guests who I did not know personally often went hand-in-hand with rejection. For every request that was reciprocated, many others went unanswered; began with excited conversations and ended with silence; or resulted in no-shows on the day of recording. While these may be some of the obvious drawbacks of working with strangers met through social media sites, it was demoralizing nonetheless.

One way to mitigate these struggles may have been to produce episodes within, or closely related to, the plant sciences. When I produced episodes within or adjacent to my area of expertise, I had a much higher success rate of guest response and retention because I directly knew, knew of, or had mutual contacts with the scientists I connected with. In addition, a narrower topic area may have made it easier to market *Hooked on Science* to a specific audience and through media outlets specific to the plant sciences. However, I chose a general audience of science lovers based on my interest in learning about a broad variety of science topics outside my area of expertise. This is not uncommon as many of the science podcasts preceding *Hooked on Science* have taken a similar approach (MacKenzie, 2019).

Podcasting is not a one-size-fits-all experience. The process was more experiential than scientific and could be difficult and isolating at times. Despite the fact that *Hooked on Science* was a collaborative interview-based podcast, much of the work was done alone behind the scenes. It was easy to feel inadequate when plays and downloads did not reflect the amount of work that went into an episode. It could also be discouraging to see celebrations of other's success on social media. While social media is a carefully curated image that only includes what people wish to share, it could be difficult to remain objective when it seemed like many of the people and podcasts I regularly interacted with were reaching impressive milestones. Balancing expectations was easier said than done because, while I wanted other creator's podcasts to do well, I wanted to see *Hooked on Science* succeed too. Over the two years I recorded and managed *Hooked on Science*, I learned a lot and I believe that future science podcasters can benefit from learning more about the opportunities and challenges that I experienced during that time.

#### **4.4. FUTURE DIRECTIONS**

Effective informal science communication is a skill that many scientists lack despite a need for direct communication between researchers and the general public. There is very little infrastructure in place in traditional graduate programs to learn about and practice the skills necessary for truly exceptional science communication. It has generally been an expectation that students come into their programs already knowing how to communicate scientific research despite little-to-no opportunities for formal training. One of the low cost and low risk ways to practice and hone science communication skills is through podcasting. For me, creating and maintaining *Hooked on Science* for two years was a labor of love, but a truly worthwhile way to learn about and practice communicating science in a novel medium. For those who are interested, podcasting should be used more readily as a method to disseminate scientific research. While creating a podcast is not a viable option for all scientists, there are many exceptional examples of science podcasts, many of which are happy to feature the research of new guests. Based on my experience alone, it was relatively easy to find a podcast to participate on as a guest, both in my discipline and outside of it. For example, of the podcasts that I was a guest on, one of the shows was plant science focused, but the premise of the other two were general science and graduate student experience. Opportunities exist for those who want to take advantage of them.

There are a few shifts in higher education that would make podcast creation more accessible to academics looking to expand their skillset and audience. It is imperative that scientists learn to communicate their science effectively under many different circumstances to a variety of audiences. Thus, more access to training from knowledgeable

science communication professionals and low-pressure scenarios to practice communicating science will immensely benefit not only students, but entire departments and colleges. In tandem, ensuring that communication methods outside of conferences and research presentations are seen as acceptable ways to disseminate research is essential to integrating new methodologies into the academic paradigm. The lack of support around alternative science communication strategies may be a barrier to entry for many individuals who are interested in pursuing podcast creation and other novel methods. Despite the many challenges associated with creating and maintaining a podcast, there are far more opportunities and benefits that arise from this endeavor. Through podcasting, individuals can expand their professional networks, develop of new soft and technical skills, and learn about relevant scientific topics in a low-pressure environment. For public-facing scientists, there are a lot of benefits to conveying scientific research to the general public and podcasting is one way to share up-to-date information in a way that is easily accessible, both in terms of comprehension and availability.

#### **4.5. TABLES AND FIGURES**

Table 4-1. Hooked on Science episodes and length by release date.

| Episode number | Release date | Episode   | Episode length |
|----------------|--------------|---|----------------|
| 0              | 2-3-20       | Ready to get Hooked on Science?                           | 2:32           |
| 1              | 2-5-20       | Wild Blueberries with Dr. Lily Calderwood                 | 31:42          |
| 2              | 2-12-20      | Cabbage and Glucobrassicin with Ilse Renner               | 28:40          |
| 3              | 2-26-20      | Kiwiberries with Seth Wannemuehler                        | 29:52          |
| 4              | 3-11-20      | Soybeans, Drones, and Iron Deficiency with Austin Dobbels | 27:09          |
| 5              | 3-25-20      | Grapes and Powdery Mildew with Anna Underhills            | 27:53          |
| 6              | 4-8-20       | Soybeans and Variable Rate Seeding with Leanna Leverich   | 33:50          |
| 7              | 5-6-20       | Video Games and National Identity with Cullan Bendig      | 34:12          |
| 8              | 5-20-20      | Theology with Dr. Jason Smith                             | 27:59          |
| 9              | 6-17-20      | Roadside Pollinator Habitat with Lauren Agnew             | 24:32          |
| 10             | 7-1-20       | Winter Oilseed Breeding with Dr. Katherine Frels          | 34:52          |
| 11             | 7-15-20      | Bacteria with Dr. Jeremy Chacon                           | 30:27          |
| 12             | 7-29-20      | Integrated Pest Management with Dr. Anna Wallingford      | 26:20          |
| 13             | 8-12-20      | Pennycress and Soybean Cyst Nematode with Cody Hoerning   | 30:43          |
| 14             | 9-16-20      | Anticoagulant Rodenticides with Dr. Carolyn Hutchinson    | 29:31          |
| 15             | 10-21-20     | Alzheimer's Disease with Mica Colmenarez                  | 26:21          |
| 17             | 11-18-20     | Deep Winter Greenhouses                                   | 49:13          |
| 18             | 12-2-20      | Salamander Habitat with Meghan Ward                       | 35:04          |
| 19             | 1-14-21      | Epigenetics and Aging with John Gonzalez                  | 32:02          |
| 20             | 2-10-21      | Multiscreening with Dr. Claire Segijn                     | 29:09          |
| 21             | 2-24-21      | Tornadoes with Alyssa Reynolds                            | 44:51          |
| 22             | 3-9-21       | Chronotype and Depression with Dustin Haraden             | 41:25          |
| 23             | 4-20-21      | Tiny Houses with Alice Wilson                             | 36:23          |
| 24             | 5-13-21      | Lucid Dreaming with Karen Konkoly                         | 25:35          |
| 25             | 5-26-21      | Bonus: Open Science with Dustin Haraden                   | 20:34          |
| 26             | 8-12-21      | Seismology with Celeste Labeledz                          | 29:20          |
| 27             | 8-26-21      | The Sociology of Tinder with Maria Stoicescu              | 42:09          |
| 28             | 9-9-21       | Water Conservation with Dr. Vikram Baliga                 | 41:14          |

|    |          |   |       |
|----|----------|---|-------|
| 29 | 9-24-21  | Bonus: Cryoseismology with Celeste Labeledz | 17:52 |
| 30 | 10-13-21 | Biomedical Engineering with Emily Schafer   | 49:59 |
| 31 | 10-28-21 | Octopus Behavior with Meghan Holst          | 57:07 |
| 32 | 12-9-21  | Weed Science with Ethan Ley                 | 45:02 |

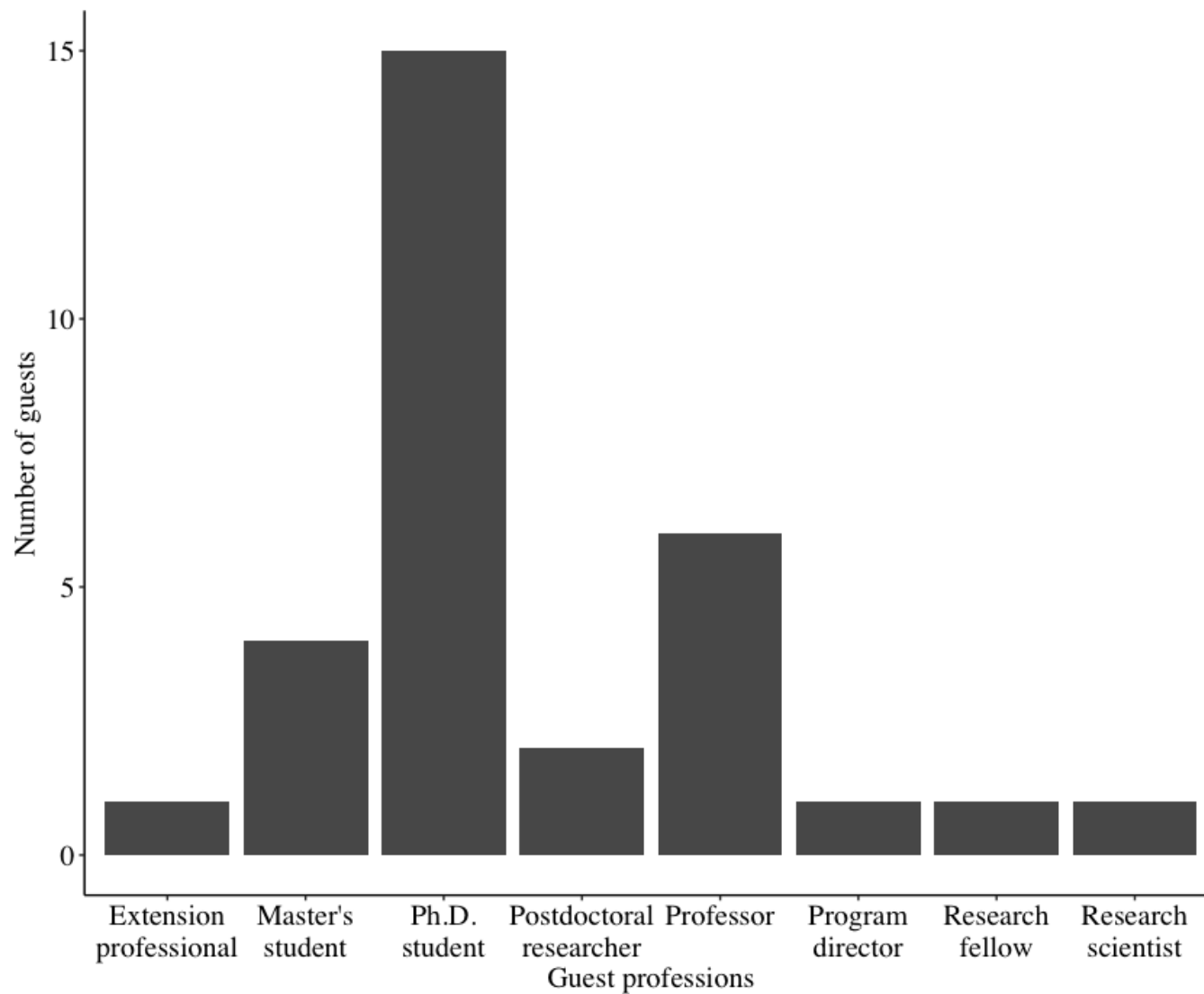


Figure 4-1. Hooked on Science guest professions by number of guests.



Figure 4-2. Examples of graphics from the Hooked on Science brand kit. Logo for distribution platforms (left) and the banner for the Facebook page (right).



## References

- Abendroth, L.J., Miguez, F.E., Castellano, M.J., Carter, P.R., Messina, C.D., Dixon, P.M., Hatfield, J.L., 2021. Lengthening of maize maturity time is not a widespread climate change adaptation strategy in the US Midwest. *Glob Chang Biol* 27, 2426–2440. <https://doi.org/10.1111/gcb.15565>
- Allen, B.L., Vigil, M.F., Jabro, J.D., 2014. Camelina Growing Degree Hour and Base Temperature Requirements. *Agron J* 106, 940–944. <https://doi.org/10.2134/agronj13.0469>
- Anderson, J. v., Wittenberg, A., Li, H., Berti, M.T., 2019. High throughput phenotyping of *Camelina sativa* seeds for crude protein, total oil, and fatty acids profile by near infrared spectroscopy. *Ind Crops Prod* 137, 501–507. <https://doi.org/10.1016/j.indcrop.2019.04.075>
- Assefa, Y., Vara Prasad, P. v., Carter, P., Hinds, M., Bhalla, G., Schon, R., Jeschke, M., Paszkiewicz, S., Ciampitti, I.A., 2016. Yield responses to planting density for US modern corn hybrids: A synthesis-analysis. *Crop Sci* 56, 2802–2817. <https://doi.org/10.2135/cropsci2016.04.0215>
- Baker, J.M., Fassbinder, J., Lamb, J.A., 2014. The Impact of Corn Stover Removal on N<sub>2</sub>O Emission and Soil Respiration: An Investigation with Automated Chambers. *Bioenergy Res* 7, 503–508. <https://doi.org/10.1007/s12155-014-9412-1>
- Baliga, V., 2021. Hops, the Science of Podcasting, and the Cult of Productivity.
- Bates, D., Mächler, M., Bolker, B.M., Walker, S.C., 2015. Fitting Linear Mixed-Effects Models Using lme4. *J Stat Softw.* <https://doi.org/10.18637/jss.v067.i01>
- Battaglia, M., Thomason, W., Fike, J.H., Evanylo, G.K., von Cossel, M., Babur, E., Iqbal, Y., Diatta, A.A., 2021. The broad impacts of corn stover and wheat straw removal for biofuel production on crop productivity, soil health and greenhouse gas emissions: A review. *GCB Bioenergy.* <https://doi.org/10.1111/gcbb.12774>
- Behnke, G.D., Villamil, M.B., 2019. Cover crop rotations affect greenhouse gas emissions and crop production in Illinois, USA. *Field Crops Res* 241. <https://doi.org/10.1016/j.fcr.2019.107580>
- Behnke, G.D., Zuber, S.M., Pittelkow, C.M., Nafziger, E.D., Villamil, M.B., 2018. Long-term crop rotation and tillage effects on soil greenhouse gas emissions and crop production in Illinois, USA. *Agric Ecosyst Environ* 261, 62–70. <https://doi.org/10.1016/j.agee.2018.03.007>
- Bender, R.R., Haegele, J.W., Below, F.E., 2015. Nutrient uptake, partitioning, and remobilization in modern soybean varieties. *Agron J* 107, 563–573. <https://doi.org/10.2134/agronj14.0435>

- Berti, M., Gesch, R., Eynck, C., Anderson, J., Cermak, S., 2016. Camelina uses, genetics, genomics, production, and management. *Ind Crops Prod.* <https://doi.org/10.1016/j.indcrop.2016.09.034>
- Berti, M., Gesch, R., Johnson, B., Ji, Y., Seames, W., Aponte, A., 2015. Double- and relay-cropping of energy crops in the northern Great Plains, USA. *Ind Crops Prod* 75, 26–34. <https://doi.org/10.1016/j.indcrop.2015.05.012>
- Berti, M., Samarappuli, D., Johnson, B.L., Gesch, R.W., 2017. Integrating winter camelina into maize and soybean cropping systems. *Ind Crops Prod* 107, 595–601. <https://doi.org/10.1016/j.indcrop.2017.06.014>
- Best, K.F., McIntyre, G.I., 1972. Studies on the flowering of *Thlaspi arvense* L. I. The influence of some environmental and genetic factors 133, 454–459.
- Blanco-Canqui, H., Ferguson, R.B., Jin, V.L., Schmer, M.R., Wienhold, B.J., Tatarko, J., 2014. Can Cover Crop and Manure Maintain Soil Properties After Stover Removal from Irrigated No-Till Corn? *Soil Science Society of America Journal* 78, 1368–1377. <https://doi.org/10.2136/sssaj2013.12.0550>
- Blanco-Canqui, H., Lal, R., 2009. Corn Stover Removal for Expanded Uses Reduces Soil Fertility and Structural Stability. *Soil Science Society of America Journal* 73, 418–426. <https://doi.org/10.2136/sssaj2008.0141>
- Brownell, S.E., Price, J. v, Steinman, L., 2013. Science Communication to the General Public: Why We Need to Teach Undergraduate and Graduate Students this Skill as Part of Their Formal Scientific Training. *The Journal of Undergraduate Neuroscience Education* 12, E6–E10.
- Canola Council of Canada, 2021. Canadian canola exports- historic. <https://www.canolacouncil.org/markets-stats/exports/#export-values> (accessed 3.16.22).
- Canola Council of Canada, 2018. When is canola “ready” to straight combine? *Canola Watch*. <https://www.canolacouncil.org/canola-watch/2018/09/12/when-is-canola-ready-to-straight-combine/> (accessed 7.18.22).
- Carlson, R.J., 2018. Continuous living cover in a corn-soybean rotation: Management approaches and environmental benefits (Master’s thesis). University of Minnesota, St. Paul, MN.
- Cherian, G., 2012. Camelina sativa in poultry diets: opportunities and challenges, in: Makkar, H.P.S. (Ed.), *Biofuel Co-Products as Livestock Feed*. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Chopra, R., Johnson, E.B., Emenecker, R., Cahoon, E.B., Lyons, J., Kliebenstein, D.J., Daniels, E., Dorn, K.M., Esfahanian, M., Folstad, N., Frels, K., McGinn, M., Ott, M., Gallaher, C., Altendorf, K., Berroyer, A., Ismail, B., Anderson, J.A., Wyse,

- D.L., Ulmasov, T., Sedbrook, J.C., David Marks, M., 2020. Identification and stacking of crucial traits required for the domestication of pennycress. *Nat Food* 1, 84–91. <https://doi.org/10.1038/s43016-019-0007-z>
- Corning, E., Sadeghpour, A., Ketterings, Q., Czymmek, K., 2016. The Carbon Cycle and Soil Organic Carbon. *Agronomy Fact Sheet Series* 2.
- Crookston, R.K., Hill, D.S., 1978. A visual indicator of the physiological maturity of soybean seed. *Crop Sci* 18, 867–870. <https://doi.org/10.2135/cropsci1978.0011183x001800050048x>
- Crop Technology Information Center, 2020. Annual Report 2019-2020: National Cover Crop Survey. West Lafayette.
- Cubins, J.A., 2019. Harvest time optimization of pennycress for use within the corn-soybean rotation (Master's thesis). University of Minnesota, St. Paul, MN.
- Cubins, J.A., Wells, M.S., Frels, K., Ott, M.A., Forcella, F., Johnson, G.A., Walia, M.K., Becker, R.L., Gesch, R.W., 2019. Management of pennycress as a winter annual cash cover crop. A review. *Agron Sustain Dev* 39. <https://doi.org/10.1007/s13593-019-0592-0>
- Cubins, J.A., Wells, S.S., Walia, M.K., Wyse, D.L., Becker, R., Forcella, F., Gardner, R.D., Johnson, G.A., Gesch, R.W., 2022. Harvest attributes and seed quality predict physiological maturity of pennycress. *Ind Crops Prod* 176, 114355. <https://doi.org/10.1016/j.indcrop.2021.114355>
- Davidson, S.M., Grunau, Z., Marcovitz, D., Gerdner, O.A., Stoklosa, J., Vestal, H.S., 2019. Narrative Podcasts as a Teaching Tool in Psychiatry. *Academic Psychiatry* 43, 275–279. <https://doi.org/10.1007/s40596-019-01062-6>
- Deng, Q., Hui, D., Chu, G., Han, X., Zhang, Q., 2017. Rain-induced changes in soil CO<sub>2</sub> flux and microbial community composition in a tropical forest of China. *Sci Rep* 7. <https://doi.org/10.1038/s41598-017-06345-2>
- Dose, H.L., Eberle, C.A., Forcella, F., Gesch, R.W., 2017. Early planting dates maximize winter annual field pennycress (*Thlaspi arvense* L.) yield and oil content. *Ind Crops Prod* 97, 477–483. <https://doi.org/10.1016/j.indcrop.2016.12.039>
- Drew, C., 2017. Edutaining audio: an exploration of education podcast design possibilities. *EMI Educ Media Int* 54, 48–62. <https://doi.org/10.1080/09523987.2017.1324360>
- Drury, C.F., Woodley, A.L., Reynolds, W.D., Yang, X.M., Phillips, L.A., Rehmann, L., Calder, W., 2021. Impacts of corn stover removal on carbon dioxide and nitrous oxide emissions. *Soil Science Society of America Journal* 85, 1334–1348. <https://doi.org/10.1002/saj2.20104>

- Dunwoody, S., Brossard, D., Dudo, A., 2009. Socialization or Rewards? Predicting U.S. Scientist-Media Interactions. *Journal Mass Commun Q* 86, 299–314.  
<https://doi.org/10.1177/107769900908600203>
- Eck, H. v., Mathers, A.C., Musick, J.T., 1987. Plant water stress at various growth stages and growth and yield of soybeans. *Field Crops Res* 17, 1–16.  
[https://doi.org/10.1016/0378-4290\(87\)90077-3](https://doi.org/10.1016/0378-4290(87)90077-3)
- Ehrensing, D.T., Guy, S.O., 2008. *Camelina*.
- Falkowski, A.R., Sparks, T.D., 2020. The Materialism Podcast: Exploring New Avenues for Materials Science Education. *Matter* 2, 276–278.  
<https://doi.org/10.1016/j.matt.2019.12.014>
- Figuroa, M., 2022. Podcasting past the paywall: How diverse media allows more equitable participation in linguistic science. *Annu Rev Appl Linguist* 42, 40–46.  
<https://doi.org/10.1017/S0267190521000118>
- Fox, J., Weisberg, S., 2019. *An R Companion to Applied Regression*, Third. ed. Sage, Thousand Oaks, CA.
- Galindo, F.S., Strock, J.S., Pagliari, P.H., 2022. Impacts of corn stover management and fertilizer application on soil nutrient availability and enzymatic activity. *Sci Rep* 12.  
<https://doi.org/10.1038/s41598-022-06042-9>
- Gesch, R.W., Archer, D.W., Berti, M.T., 2014. Dual cropping winter camelina with soybean in the northern corn belt. *Agron J* 106, 1735–1745.  
<https://doi.org/10.2134/agronj14.0215>
- Gesch, R.W., Cermak, S.C., 2011. Sowing date and tillage effects on fall-seeded *Camelina* in the Northern Corn Belt. *Agron J* 103, 980–987.  
<https://doi.org/10.2134/agronj2010.0485>
- Gesch, R.W., Johnson, J.M.F., 2015. Water use in camelina-soybean dual cropping systems. *Agron J* 107, 1098–1104. <https://doi.org/10.2134/agronj14.0626>
- Gesch, R.W., Royo-Esnal, A., Edo-Tena, E., Recasens, J., Isbell, T.A., Forcella, F., 2016. Growth environment but not seed position on the parent plant affect seed germination of two *Thlaspi arvense* L. populations. *Ind Crops Prod* 84, 241–247.  
<https://doi.org/10.1016/j.indcrop.2016.02.006>
- Grady, K., Nleya, T., 2010. *Camelina Production*.
- Gugel, R.K., Falk, K.C., 2006. Agronomic and seed quality evaluation of *Camelina sativa* in western Canada. *Canadian Journal of Plant Science* 86, 1047–1058.  
<https://doi.org/10.4141/P04-081>

- Guoju, Xiao, Fengju, Zhang, C., Luo, 2012. The relationship between winter temperature rise and soil fertility properties. *Air, Soil and Water Research* 5, 15–22. <https://doi.org/10.1177/ASWR.S8599>
- Haraden, D., McCormick, K., 2021. Pyramid Scheme Realness: Communicating your science with Julija Cubins.
- Heaton, E.A., Schulte, L.A., Berti, M., Langeveld, H., Zegada-Lizarazu, W., Parrish, D., Monti, A., 2013. Managing a second-generation crop portfolio through sustainable intensification: Examples from the USA and the EU. *Biofuels, Bioproducts and Biorefining* 7, 702–714. <https://doi.org/10.1002/bbb>
- Heggenstaller, A.H., Anex, R.P., Liebman, M., Sundberg, D.N., Gibson, L.R., 2008. Productivity and nutrient dynamics in bioenergy double-cropping systems. *Agron J* 100, 1740–1748. <https://doi.org/10.2134/agronj2008.0087>
- Hoerning, C., Wells, M.S., Gesch, R., Forcella, F., Wyse, D., 2020. Yield tradeoffs and weed suppression in a winter annual oilseed relay-cropping system. *Agron J* 112, 2485–2495. <https://doi.org/10.1002/agj2.20160>
- Hojilla-Evangelista, M.P., Evangelista, R.L., Isbell, T.A., Selling, G.W., 2013. Effects of cold-pressing and seed cooking on functional properties of protein in pennycress (*Thlaspi arvense* L.) seed and press cakes. *Ind Crops Prod* 45, 223–229. <https://doi.org/10.1016/j.indcrop.2012.12.026>
- Hojilla-Evangelista, M.P., Selling, G.W., Berhow, M.A., Evangelista, R.L., 2015. Extraction, composition and functional properties of pennycress (*Thlaspi arvense* L.) press cake protein. *JAOCs, Journal of the American Oil Chemists' Society* 92, 905–914. <https://doi.org/10.1007/s11746-015-2653-0>
- Hothorn, T., Bretz, F., Westfall, P., 2008. Simultaneous Inference in General Parametric Models. *Biometrical Journal* 50, 346–363.
- Hunter, J., Roth, G.W., 2010. Camelina Production and Potential in Pennsylvania. PennState Extension. <https://extension.psu.edu/camelina-production-and-potential-in-pennsylvania> (accessed 1.5.22).
- Johnson, G.A., Wells, M.S., Anderson, K., Gesch, R.W., Forcella, F., Wyse, D.L., 2017. Yield tradeoffs and nitrogen between pennycress, camelina, and soybean in relay- and double-crop systems. *Agron J* 109, 2128–2135. <https://doi.org/10.2134/agronj2017.02.0065>
- Kim, S., Dale, B.E., Jenkins, R., 2009. Life cycle assessment of corn grain and corn stover in the United States. *International Journal of Life Cycle Assessment* 14, 160–174. <https://doi.org/10.1007/s11367-008-0054-4>
- Kleba, S., Ismail, B.P., 2018. Report on Minnesota Plant Based Proteins for Food. Crookston, MN.

- Knezevic, S.Z., Evans, S.P., Mainz, M., 2003. Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). *Weed Technology* 17, 666–673. <https://doi.org/10.1614/wt02-49>
- Kuehne, L.M., Twardochleb, L.A., Fritschie, K.J., Mims, M.C., Lawrence, D.J., Gibson, P.P., Stewart-Koster, B., Olden, J.D., 2014. Practical science communication strategies for graduate students. *Conservation Biology* 28, 1225–1235. <https://doi.org/10.1111/cobi.12305>
- Lawrence, R.D., Anderson, J.L., Clapper, J.A., 2016. Evaluation of camelina meal as a feedstuff for growing dairy heifers. *J Dairy Sci* 99, 6215–6228. <https://doi.org/10.3168/jds.2016-10876>
- Lenth, R. v., Buerkner, P., Herve, M., Love, J., Miguez, F., Riebl, H., Singmann, H., 2022. Package “emmeans.”
- Li, X., Mupondwa, E., 2016. Production and value-chain integration of camelina sativa as a dedicated bioenergy feedstock in the Canadian prairies, in: 24th European Biomass Conference and Exhibition. Amsterdam, The Netherlands, pp. 151–157.
- LI-COR, 2003. 6400-09 Soil CO<sub>2</sub> Flux Chamber Instruction Manual.
- Lim, M., Swenson, R., 2021. Talking Plants: Examining the Role of Podcasts in Communicating Plant Pathology Knowledge. *Journal of Applied Communications* 105. <https://doi.org/10.4148/1051-0834.2366>
- Luna, G., Cullen, D., 2011. Podcasting as Complement to Graduate Teaching: Does it Accommodate Adult Learning Theories? *International Journal of Teaching and Learning in Higher Education* 23, 40–47.
- MacKenzie, L.E., 2019. Science podcasts: Analysis of global production and output from 2004 to 2018. *R Soc Open Sci* 6. <https://doi.org/10.1098/rsos.180932>
- Malecki, S.L., Quinn, K.L., Zilbert, N., Razak, F., Ginsburg, S., Verma, A.A., Melvin, L., 2019. Understanding the use and perceived impact of a medical podcast: Qualitative study. *JMIR Med Educ* 5. <https://doi.org/10.2196/12901>
- Malhi, S.S., Johnson, E.N., Hall, L.M., May, W.E., Phelps, S., Nybo, B., 2014. Effect of nitrogen fertilizer application on seed yield, N uptake, and seed quality of *Camelina sativa*. *Can J Soil Sci* 94, 35–47. <https://doi.org/10.4141/CJSS2012-086>
- Martinelli, T., Galasso, I., 2011. Phenological growth stages of *Camelina sativa* according to the extended BBCH scale. *Annals of Applied Biology* 158, 87–94. <https://doi.org/10.1111/aab.12163>
- McClung, S., Johnson, K., 2010. Examining the motives of podcast users. *Journal of Radio and Audio Media* 17, 82–95. <https://doi.org/10.1080/19376521003719391>
- McVay, K.A., Lamb, P.F., 2008. *Camelina Production in Montana*.

- Midwest Cover Crops Council, 2018. Cover Crop Decision Tool.  
<https://midwestcovercrops.org/covercroptool/> (accessed 9.4.22).
- Mirsky, S.B., Curran, W.S., Mortensen, D.A., Ryan, M.R., Shumway, D.L., 2009.  
Control of cereal rye with a roller/crimper as influenced by cover crop phenology.  
*Agron J* 101, 1589–1596. <https://doi.org/10.2134/agronj2009.0130>
- Moser, B.R., 2012. Biodiesel from alternative oilseed feedstocks: camelina and field pennycress. *Biofuels* 3, 193–209. <https://doi.org/10.4155/bfs.12.6>
- Mousavi-Avval, S.H., Shah, A., 2020. Techno-economic analysis of pennycress production, harvest and post-harvest logistics for renewable jet fuel. *Renewable and Sustainable Energy Reviews* 123. <https://doi.org/10.1016/j.rser.2020.109764>
- Muhammad, I., Sainju, U.M., Zhao, F., Khan, A., Ghimire, R., Fu, X., Wang, J., 2019. Regulation of soil CO<sub>2</sub> and N<sub>2</sub>O emissions by cover crops: A meta-analysis. *Soil Tillage Res* 192, 103–112. <https://doi.org/10.1016/j.still.2019.04.020>
- Natelson, R.H., Wang, W.C., Roberts, W.L., Zering, K.D., 2015. Technoeconomic analysis of jet fuel production from hydrolysis, decarboxylation, and reforming of camelina oil. *Biomass Bioenergy* 75, 23–34.  
<https://doi.org/10.1016/j.biombioe.2015.02.001>
- National Centers for Environmental Information, 2021. U.S. Climate Normals.  
<https://www.ncei.noaa.gov/access/us-climate-normals/> (accessed 7.22.21).
- Negassa, W., Price, R.F., Basir, A., Snapp, S.S., Kravchenko, A., 2015. Cover crop and tillage systems effect on soil CO<sub>2</sub> and N<sub>2</sub>O fluxes in contrasting topographic positions. *Soil Tillage Res* 154, 64–74. <https://doi.org/10.1016/j.still.2015.06.015>
- Nisbet, M.C., Scheufele, D.A., 2009. What’s next for science communication? promising directions and lingering distractions. *Am J Bot* 96, 1767–1778.  
<https://doi.org/10.3732/ajb.0900041>
- O’Brien, P.L., Sauer, T.J., Archontoulis, S., Karlen, D.L., Laird, D., 2020. Corn stover harvest reduces soil CO<sub>2</sub> fluxes but increases overall C losses. *GCB Bioenergy* 12, 894–909. <https://doi.org/10.1111/gcbb.12742>
- Osborne, S.L., Johnson, J.M.F., Jin, V.L., Hammerbeck, A.L., Varvel, G.E., Schumacher, T.E., 2014. The Impact of Corn Residue Removal on Soil Aggregates and Particulate Organic Matter. *Bioenergy Res* 7, 559–567.  
<https://doi.org/10.1007/s12155-014-9413-0>
- Ott, M.A., Eberle, C.A., Thom, M.D., Archer, D.W., Forcella, F., Gesch, R.W., Wyse, D.L., 2019. Economics and agronomics of relay-cropping pennycress and camelina with soybean in Minnesota. *Agron J* 111, 1281–1292.  
<https://doi.org/10.2134/agronj2018.04.0277>

- Patel, S., Lenssen, A.W., Moore, K.J., Mohammed, Y.A., Gesch, R.W., Wells, M.S., Johnson, B.L., Berti, M.T., Matthees, H.L., 2021. Interseeded pennycress and camelina yield and influence on row crops. *Agron J*.  
<https://doi.org/10.1002/agj2.20655>
- Picardi, I., Regina, S., 2008. Science via podcast. *Journal of Science Communication* 7.
- Plavén-Sigra, P., Matheson, G.J., Schiffler, B.C., Thompson, W.H., 2017. The readability of scientific texts is decreasing over time. *Elife* 6.  
<https://doi.org/10.7554/eLife.27725>
- R Core Team, 2021. R: A language and environment for statistical computing.  
<https://www.R-project.org/> (accessed 6.1.21).
- Randall, G.W., Vetsch, J.A., 2005. Nitrate losses in subsurface drainage from a corn-soybean rotation as affected by fall and spring application of nitrogen and nitrapyrin. *J Environ Qual* 34, 590–597. <https://doi.org/10.2134/jeq2005.0590>
- Ray, R.L., Griffin, R.W., Fares, A., Elhassan, A., Awal, R., Woldesenbet, S., Risch, E., 2020. Soil CO<sub>2</sub> emission in response to organic amendments, temperature, and rainfall. *Sci Rep* 10, 1–14. <https://doi.org/10.1038/s41598-020-62267-6>
- Reth, S., Reichstein, M., Falge, E., 2005. The effect of soil water content, soil temperature, soil pH-value and the root mass on soil CO<sub>2</sub> efflux - A modified model. *Plant Soil* 268, 21–33. <https://doi.org/10.1007/s11104-005-0175-5>
- Riddell, J.C., Robins, L., Lin M, Sherbino J, Keck, I.J./, 2020. Hearing Is Believing: A Qualitative Exploration of Trust and Credibility Judgements in Educational Podcasts, *Annals of Emergency Medicine*.
- Robson, M., 2021. Intimacy in isolation: Podcasting, affect, and the pandemic. *Perspect Biol Med* 64, 388–407. <https://doi.org/10.1353/pbm.2021.0031>
- Roesch-McNally, G.E., Basche, A.D., Arbuckle, J.G., Tyndall, J.C., Miguez, F.E., Bowman, T., Clay, R., 2017. The trouble with cover crops: Farmers’ experiences with overcoming barriers to adoption. *Renewable Agriculture and Food Systems* 33, 1–12. <https://doi.org/10.1017/S1742170517000096>
- Rotundo, J.L., Miller-Garvin, J.E., Naeve, S.L., 2016. Regional and temporal variation in soybean seed protein and oil across the United States. *Crop Sci* 56, 797–808.  
<https://doi.org/10.2135/cropsci2015.06.0394>
- Rotundo, J.L., Westgate, M.E., 2009. Meta-analysis of environmental effects on soybean seed composition. *Field Crops Res* 110, 147–156.  
<https://doi.org/10.1016/j.fcr.2008.07.012>
- Royo-Esnal, A., Edo-Tena, E., Torra, J., Recasens, J., Gesch, R.W., 2017. Using fitness parameters to evaluate three oilseed Brassicaceae species as potential oil crops in

- two contrasting environments. *Ind Crops Prod* 95, 148–155.  
<https://doi.org/10.1016/j.indcrop.2016.10.020>
- Royo-Esnal, A., Valencia-Gredilla, F., 2018. Camelina as a rotation crop for weed control in organic farming in a semiarid mediterranean climate. *Agriculture (Switzerland)* 8. <https://doi.org/10.3390/agriculture8100156>
- Russo, V.M., Bruton, B.D., Sams, C.E., 2010. Classification of temperature response in germination of Brassicas. *Ind Crops Prod* 31, 48–51.  
<https://doi.org/10.1016/j.indcrop.2009.08.007>
- Schafer, E., 2021. Winter Oilseed Planting in the Spotlight- CROSSOVER with Hooked on Science.
- Scheufele, D.A., 2013. Communicating science in social settings. *Proc Natl Acad Sci U S A* 110, 14040–14047. <https://doi.org/10.1073/pnas.1213275110>
- Sedbrook, J.C., Phippen, W.B., Marks, M.D., 2014. New approaches to facilitate rapid domestication of a wild plant to an oilseed crop: Example pennycress (*Thlaspi arvense* L.). *Plant Science* 227, 122–132.  
<https://doi.org/10.1016/j.plantsci.2014.07.008>
- Sindelar, A.J., Schmer, M.R., Gesch, R.W., Forcella, F., Eberle, C.A., Thom, M.D., Archer, D.W., 2017. Winter oilseed production for biofuel in the US Corn Belt: opportunities and limitations. *GCB Bioenergy* 9, 508–524.  
<https://doi.org/10.1111/gcbb.12297>
- Solis, A., Vidal, I., Paulino, L., Johnson, B.L., Berti, M.T., 2013. Camelina seed yield response to nitrogen, sulfur, and phosphorus fertilizer in South Central Chile. *Ind Crops Prod* 44, 132–138. <https://doi.org/10.1016/j.indcrop.2012.11.005>
- Sustainable Agriculture Research & Education program, 2012. *Managing Cover Crops Profitably*, 3rd ed, *Managing Cover Crops Profitably*. United Book Press, Inc., College Park, MD.
- Svečnjak, Z., Rengel, Z., 2006. Canola cultivars differ in nitrogen utilization efficiency at vegetative stage. *Field Crops Res* 97, 221–226.  
<https://doi.org/10.1016/j.fcr.2005.10.001>
- Tan, S., Ni, X., Yue, K., Liao, S., Wu, F., 2021. Increased precipitation differentially changed soil CO<sub>2</sub> efflux in arid and humid areas. *Geoderma* 388.  
<https://doi.org/10.1016/j.geoderma.2021.114946>
- Taylor, M.Z., 2009. Podcast lectures as a primary teaching technology: Results of a one-year trial. *Journal of Political Science Education* 5, 119–137.  
<https://doi.org/10.1080/15512160902816249>
- Edison Research, 2022. *The Infinite Dial 2022*.

- University of Minnesota Extension, 2021. Guide to planting cover crops in Minnesota. <https://extension.umn.edu/cover-crops/planting-cover-crops#what-is-my-crop-rotation-and-harvest-timing%3F--714210> (accessed 3.23.22).
- USDA Agricultural Research Service, 2012. USDA Plant Hardiness Zone Map. <https://planthardiness.ars.usda.gov/> (accessed 5.24.22).
- USDA Economic Research Service, 2021a. Interactive Visualization: U.S. Commodity Costs and Returns by Region and by Commodity. <https://www.ers.usda.gov/data-products/commodity-costs-and-returns/interactive-visualization-u-s-commodity-costs-and-returns-by-region-and-by-commodity/> (accessed 4.9.22).
- USDA Economic Research Service, 2021b. Commodity Costs and Returns Documentation. <https://www.ers.usda.gov/data-products/commodity-costs-and-returns/documentation/> (accessed 4.9.22).
- USDA Foreign Agricultural Service, 2022. Oilseeds: World markets and trade. Washington, D.C.
- USDA Foreign Agricultural Service, 2020. Oilseeds: World markets and trade. Washington, D.C.
- USDA Foreign Agricultural Service, 2019. Oilseeds: World markets and trade. Washington, D.C.
- USDA Foreign Agricultural Service, 2018. Oilseeds: World markets and trade. Washington, D.C.
- USDA National Agricultural Statistics Service, 2022. Prices Received: Corn Prices Received by Month, US. [https://www.nass.usda.gov/Charts\\_and\\_Maps/Agricultural\\_Prices/pricecn.php](https://www.nass.usda.gov/Charts_and_Maps/Agricultural_Prices/pricecn.php) (accessed 4.9.22).
- USDA National Agricultural Statistics Service, 2021a. Minnesota Ag News- 2020 Soybean County Estimates.
- USDA National Agricultural Statistics Service, 2021b. Minnesota Ag News- 2020 Corn County Estimates. St. Paul.
- USDA National Agricultural Statistics Service, 2021c. 2020 State Agricultural Overview. [https://www.nass.usda.gov/Quick\\_Stats/Ag\\_Overview/stateOverview.php?state=MINNESOTA](https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=MINNESOTA) (accessed 4.27.21).
- USDA National Agricultural Statistics Service, 2010. Field crops: Usual planting and harvesting dates.
- Walia, M.K., Wells, M.S., Cubins, J., Wyse, D., Gardner, R.D., Forcella, F., Gesch, R., 2018. Winter camelina seed yield and quality responses to harvest time. *Ind Crops Prod* 124, 765–775. <https://doi.org/10.1016/j.indcrop.2018.08.025>

- Wall, D., Mulla, D., Weiss, S., Wasley, D., Pearson, T.E., Henningsgaard, B., 2013. Nitrogen in Minnesota Surface Waters. St. Paul.
- Wallander, S., Smith, D., Bowman, M., Claassen, R., 2021. Cover Crop Trends, Programs, and Practices in the United States.
- Wells, M.S., Brinton, C.M., Reberg-Horton, S.C., 2016. Weed suppression and soybean yield in a no-till cover-crop mulched system as influenced by six rye cultivars. *Renewable Agriculture and Food Systems* 31, 429–440. <https://doi.org/10.1017/S1742170515000344>
- Wells, M.S., Reberg-Horton, S.C., Mirsky, S.B., 2014. Cultural Strategies for Managing Weeds and Soil Moisture in Cover Crop Based No-Till Soybean Production. *Weed Sci* 62, 501–511. <https://doi.org/10.1614/ws-d-13-00142.1>
- Weyers, S., Thom, M., Forcella, F., Eberle, C., Matthees, H., Gesch, R., Ott, M., Feyereisen, G., Strock, J., Wyse, D., 2019. Reduced Potential for Nitrogen Loss in Cover Crop-Soybean Relay Systems in a Cold Climate. *J Environ Qual* 48, 660–669. <https://doi.org/10.2134/jeq2018.09.0350>
- Weyers, S.L., Gesch, R.W., Forcella, F., Eberle, C.A., Thom, M.D., Matthees, H.L., Ott, M., Feyereisen, G.W., Strock, J.S., 2021. Surface runoff and nutrient dynamics in cover crop–soybean systems in the Upper Midwest. *J Environ Qual* 50, 158–171. <https://doi.org/10.1002/jeq2.20135>
- Wilhelm, W.W., Doran, J.W., Power, J.F., 1986. Corn and Soybean Yield Response to Crop Residue Management Under No-Tillage Production Systems 1. *Agron J* 78, 184–189. <https://doi.org/10.2134/agronj1986.00021962007800010036x>
- Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B., Linden, D.R., 2004. Crop and Soil Productivity Response to Corn Residue Removal: A Literature Review. *Agron J* 96, 1–17. <https://doi.org/10.2134/agronj2004.0001>
- Wittenberg, A., Anderson, J. v., Berti, M.T., 2020. Crop growth and productivity of winter camelina in response to sowing date in the northwestern Corn Belt of the USA. *Ind Crops Prod* 158. <https://doi.org/10.1016/j.indcrop.2020.113036>
- Woyengo, T.A., Patterson, R., Slominski, B.A., Beltranena, E., Zijlstra, R.T., 2016. Nutritive value of cold-pressed camelina cake with or without supplementation of multi-enzyme in broiler chickens. *Poult Sci* 95, 2314–2321. <https://doi.org/10.3382/ps/pew098>
- Ye, Y., 2021. From abstracts to “60-second science” podcasts: Reformulation of scientific discourse. *J Engl Acad Purp* 53, 101025. <https://doi.org/10.1016/j.jeap.2021.101025>